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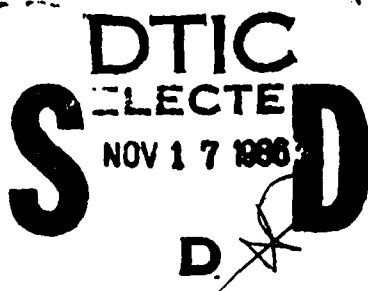S D
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THROUGH THE ICE
MINING STUDY

FINAL REPORT

June 1983

Prepared under
Contract No. N60921-83-D-0002

Prepared by
Epoch Engineering, Inc.
702 Russell Avenue
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A search for literature relevant to ice penetration by naval mines has shown that interest in the problem has existed since 1952, and has continued to the present time. Early studies were followed by Arctic sea ice penetration tests utilizing instrumented penetrators of varying sizes and weights. Empirical equations for prediction of ice penetration and longitudinal accelerations during ice penetration were originally developed by modification of earth penetration equations. Analysis of all available test data has validated the empirical equations within the originally stated limits of accuracy. Comparable test data appear to confirm the validity for structural tests of penetration testing in gypsite as a simulation of Arctic sea ice for the first few feet of penetration. Very little information exists concerning transverse acceleration and loading in either ice or gypsite. Parametric studies of mine design parameters for a typical moored mine with practical constraints show trends of the weight area factor relationship and the nose shape factor relationship to maximum thickness of ice perforation capability, the payload to penetration relationship and the weight efficiency of the payload in a constrained total weight system. The few data available suggest that the problem of structural survival of transverse loads may be far more severe than that of surviving the longitudinal deceleration forces.

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CHAPTER 1

INTRODUCTION

1.1 PURPOSE

1.1.1 The purpose of this report is to present a concise synopsis of previous investigations of ice penetration which are relevant to naval mines, to provide a reader's guide to pertinent existing literature, to present a discussion and analysis of the information in the literature, and to provide parametric studies of mine design parameters relative to ice penetration which will be of value to the mine designer.

1.2 BACKGROUND

1.2.1 Interest in the capability to conduct naval mining operations in the Arctic was initiated about three decades ago and has grown with further development of the capability and utility of operation of submarines under the Arctic ice cover. Concurrently, Arctic environmental research and also Arctic commercial operations have greatly increased the knowledge of the Arctic environment. Growth of the strategic importance of under-ice operational capabilities of missile-carrying submarines has further contributed to interest in the capability of ice penetration by naval mines.

1.2.2 Initial investigation of ice penetration was largely by laboratory experiment and theoretical study.

1.2.3 In a completely separate endeavor, extensive effort was devoted to terradynamics investigation, the investigation of earth (soil and rock) penetration by weapons. A technology for earth penetration study was developed, and empirical equations for earth penetration prediction were formulated and validated with data from many tests with varied parameters of the penetrator vehicles and the earth targets.

1.2.4 Sea Ice Penetrometer (SIP) development under the auspices of the U.S. Coast Guard provided experience in ice penetration test operations in the Arctic and data concerning Arctic sea ice penetration. The SIP was an air-dropped, slender, pointed vehicle weighing approximately 50 pounds which penetrated the ice cover by its own inertia. Instrumentation sensed decelerations as the vehicle penetrated the ice and telemetered the information to a receiving station in the drop aircraft. Analysis of deceleration vs. time data permitted determination of ice thickness to $\pm$ 3 inches.

1.2.5 Next, development and testing of an ice penetrating sensor vehicle, which was larger and heavier than the SIP, provided further valuable additions to the still small fund of knowledge concerning ice penetration.

1.2.6 Starting in fiscal year 1973, effort was devoted to utilization of the ice penetration data from these small penetrators in an attempt to reconcile ice penetration with earth penetration technology, to develop empirical relationships which could become the basis of ice penetration technology for ordnance items, and to validate those empirical relationship equations first with data from the smaller vehicles and later with data from tests of full-size mines and mine-like test items. In the subsequent years a number of coordinated studies, investigations, analyses, and Arctic tests have contributed to the state of ice penetration technology as it exists today. Despite the number of years of interest in Arctic mining, the number of tests in the Arctic have been quite limited because of the complexity, difficulty and cost. As a consequence, ice penetration technology has depended as much as possible on related earth penetration technology for its foundation.

1.2.7 Because of the complexity, difficulty and cost of testing in the Arctic, the interdependence on other Arctic test operations, seasonal limitations, etc., there was investigation of the suitability of other more economical test sites for simulation of Arctic sea ice penetration. Penetration testing in gypsite deposits in the White Sands Missile Range (WSMR), New Mexico was validated for structural tests for the first few feet only of ice penetration.

1.3 ORGANIZATION OF THE REPORT

1.3.1 Chapter 2 of this report is a discussion and listing of the results of a search of the literature relevant to ice penetration by naval mines.

1.3.2 Appendix (A) is a complete listing of the documents found which were considered pertinent to the purpose of this report. A short resume of the content of each document will lead the interested reader to the complete data, test results, and post-test analyses.

1.3.3 Chapter (3) is a discussion of the significance of the information found in the literature and an analysis of the agreement between experimental data and empirical equations plus a limited analysis of the simulation of Arctic sea ice penetration tests by tests in gypsite.

1.3.4 Chapter (4) contains the results of general parametric studies of the most important mine design factors pertaining to ice penetration with examination of the effect of their variations within practical limitations. They indicate optimum geometric relationships and can be utilized by the mine designer when considered with the specific constraints and design objectives/requirements of a particular design problem.

1.3.5 Chapter (5) consists of a summary and conclusions.

CHAPTER 2
LITERATURE REVIEW

2.1 FIRST MINE PLANTS THROUGH ICE

2.1.1 The first test planting of mines through ice was reported in reference (1). The test, called "Project ICE CUBE," was conducted by the Bureau of Ordnance (BuOrd Re7a) in February/March 1954 with the assistance of Mining Squadron VP-21, the Naval Ordnance Laboratory (NOL) and the U.S. Army Corps of Engineering Station, Houghton, Michigan. Apparently, the investigation was in response to an action assignment to BuOrd from the Mine Warfare Conference of December 1952 concerning the suitability of dropping mines on ice.

2.1.2 Seven stockpile parachute retarded mines Mk 25 and 36 plus four stockpile free-fall mines Mk 39 were planted through 16 to 24 inches thick ice into Portage Lake, Michigan. The retarded mines approached the ice in a near vertical trajectory and perforated a neat hole about 25 inches in diameter. The free fall Mk 39 mines had an impact angle of about 45 degrees and created a hole in the ice about 19 feet by 24 feet which was filled with large chunks of ice. The mines contained no test instrumentation. It is believed that the mines were never recovered.

2.2 STANFORD RESEARCH INSTITUTE INVESTIGATIONS

2.2.1 Beginning in 1965, the Naval Warfare Research Center of Stanford Research Institute (SRI), Menlo Park, California performed a number of laboratory investigations and theoretical studies of ice penetration under Office of Naval Research contracts monitored by NOL (Mr. M. M. Kleinerman). Small diameter penetrators were propelled into ice slabs; one field test was performed with larger diameter models and real Arctic sea ice. Theoretical studies of the mechanics of penetration and perforation of Arctic sea ice were performed and a computer code

2-1

was developed. In addition, consideration was given to the employment of shaped charges as a means of achieving perforation in the Arctic sea ice cover. Four reports, references (2) through (5) record the work performed between 1965 and 1970.

2.3 SANDIA LABORATORIES INVESTIGATIONS

2.3.1 The dominant and more recent investigations of ice penetration by naval mines have been conducted by Sandia Laboratories in conjunction with the Naval Surface Weapons Center (NSWC) Arctic Program Office. Sandia's background and experience in terradynamics and earth penetration investigations provided a valuable foundation, in addition to the earlier SRI studies.

2.3.2 The Office of Research and Development of the U.S. Coast Guard (USCG) funded Sandia in 1970 to begin development of an air-delivered sea-ice penetrometer. The purpose of the device was to measure remotely the thickness of sea ice, which was accomplished by sensing deceleration during ice penetration, telemetering the data in real time to a recorder on board the drop aircraft, and twice integrating the deceleration-time-record to determine the distance traveled in the ice or the ice thickness. Feasibility tests in the Arctic were performed in 1970 and development tests in the Arctic were made in 1971. References (6) and (7) record the development and Arctic testing of the sea ice penetrometer.

2.3.3 Another portion of the coordinated Arctic test program which contributed to the development of the ice penetration technology was field testing of the ice penetrating sensor vehicle. Early design and development of the sensor vehicle had been by AC Electronics Division of General Motors Corporation with Naval Air Systems Command funding sponsorship. In 1971-72, Sandia Laboratories performed a study for NOL to determine and evaluate those parameters that affect the implant performance of an air delivered ice penetrating sensor vehicle. Reference (8) presents the results of the parametric study which considered parameters such as vehicle shapes and weights, ice thicknesses, impact angles and velocities, etc. Successful feasibility tests were conducted in the Arctic in 1973 and Arctic development tests were in 1975. References (9) and (10) present development history, test information and data.

2.3.4 While the main objective of the program was to develop an ice penetration technology rather than a specific ice penetrating weapon, advantage was taken of the opportunity to investigate the ice penetrating capabilities of some existing mine and destructor shapes by including a small number of samples in the coordinated Arctic tests. Data from these larger and heavier stuctures provided valuable additions to the previously available ice penetration information, plus the obviously valuable basic demonstration of the ice penetrating capabilities of these mines. Reference (11) is a report of test of an 8 inch diameter, 360 pound scale model of a slant-nose blunt bottom mine configuration during the April 1973 Arctic test. Seven Mk 82 and one Mk 84 dummy bombs were dropped in the Arctic tests in April 1975. Varied impact angles were investigated and decelerations were measured. Test data and results are recorded in reference (12).

2.3.5 All of the ice penetration technology studies and tests were contributory to the general objective of developing an understanding of the ice penetration phenomenon so that the ice penetration characteristics of ordnance items could be predicted. In reference (13), Sandia reported the results of a study of all existing ice penetration test data and presented modified empirical equations for the prediction of penetration depth, average deceleration and peak deceleration of air dropped projectiles when ice perforation does not occur. Similar equations were presented for the prediction of average and peak deceleration plus velocity change for the situation when complete perforation does occur. References (14) and (15) are letter reports which present analyses and predictions of the sea ice penetration/perforation characteristics of selected mines and bomb shapes. Predictions were later compared with test results in the post-test analyses in reference (12). Reference (16) is a letter status report and pre-test planning document prior to the April 1973 Arctic test.

2.3.6 Part of the program in 1976 and 1977 was an investigation of the possibility of more economical simulation of Arctic sea ice tests in a more accessible location. Comparison data of ice penetration tests in the Arctic and tests in gypsite at the White Sands Missile Range (WSMR) were analyzed and results were reported in reference (17). The data and analyses of additional mine structural tests in gypsite are contained in references (17) and (18).

2.3.7 After some test information concerning the ice penetration characteristics of sea bottom mines had become available, the almost complete lack of information pertaining to the structurally "softer" moored mines was obvious. The investigation of the ice penetration characteristics of a typical soft mine was reported in references (19), (20), (21).

2.3.8 In 1981/1982, Sandia performed a study to evaluate the applicability to the ice penetration problem of more recent analytical methods for predicting earth penetration. An ice penetration model was developed and used to calculate penetrator performance and loading for several ice penetration tests. The calculations were then compared to the Arctic test experimental data. The study results were reported in reference (22).

2.4 ANNUAL CONFERENCE ON THE NAVAL MINEFIELD

2.4.1 Papers related to Arctic Mining have been occasionally presented in annual conferences on the naval minefield. The general theme of the fourteenth conference was ICE COVER. NOLTR 71-71, reference (23), is the record of that conference. A paper entitled "An Air-Dropped Sea Ice Penetrometer" by C. W. Young and LCdr. J. W. McIntosh, USCG presented information about penetrometer development. Reference (24), a paper entitled "The Design of a Large Shaped Charge Suitable for the Penetration of Arctic Sea Ice" by J. M. Jones of the Defense Research Establishment, Valcartier, Quebec, Canada, was reviewed at the conference. In the literature review, explosive shaped charge penetration seems to have periodically come to mind as the way to achieve ice penetration by mines. This reference is included as an example of an investigation of that approach with some explanation of the disadvantages.

2.5 ARCTIC MINING CAPABILITIES AND REQUIREMENTS

2.5.1 Reference (25) is a report prepared for the purpose of providing information with which to complete a draft Operational Requirement for an Arctic mine and to outline a course of action to respond to the operational requirement. It represents a joint effort of Mine Warfare Command, Naval Surface Weapons Center and the Office of Naval Research.

2.6 OTHER STUDIES

2.6.1 Reference (26) is a memorandum of results of a study of the ability of the SUBROC Depth Bomb to penetrate Arctic ice fields with predictions of probable induced shock levels from ice penetrations.

2.7 RELEVANT LITERATURE

2.7.1 Appendix (A) is included to provide the reader with a complete list of the literature found pertinent to the purpose of this report. A brief description of the content of each document is included, which can lead the interested reader to the complete data, individual test results and post-test analyses. Sources were the Naval Surface Weapons Center, White Oak, Technical Library, the Arctic Systems Office (U401) and the Mechanical Design Branch (U13). A search in the Scientific and Technical Intelligence Liaison Office (STILO) did not reveal any literature not previously known or available to the Arctic Systems Office.

2.7.2 It might be informative to include a brief note that there are other connotations of the words "ice penetration" which lead to valid bodies of literature but not pertinent to the purpose of this report. Examples are: ice penetration by mechanical drilling, by hydraulic jet, by thermal probe, by an ice-breaker (ship), by a submarine rising from below the surface, from the viewpoint of destroying an ice bridge across a river, etc. - - -.

CHAPTER 3
DISCUSSION AND ANALYSIS

3.1 INTRODUCTION

3.1.1 In Chapter 2, an overview was presented of the references relevant to investigations and tests of ice penetration by naval mines (or similar ice penetrators). A discussion of the present significance of the information and an analysis of the agreement between all pertinent test data and the empirical equations will be presented in this chapter.

3.2 DISCUSSION

3.2.1 The investigations relevant to ice penetration by naval mines have been performed primarily by three organizations - the Naval Surface Weapons Center, Stanford Research Institute and Sandia Laboratories. Support has been provided by many other groups. The SRI and Sandia work was either monitored by or funded by NSWC.

3.2.2 SRI investigations were conducted in 1965 to 1970. The early experimental tests were performed with small (5/16 inch to 1-1/4 inch) diameter penetrators and laboratory produced ice slabs. Rifle and gun powered projectile launchers were developed to provide higher velocities for larger (up to 6 inch) diameter penetrators. Techniques and procedures for laboratory production of simulated Arctic sea ice were improved. One test was conducted with the projectile launchers in the Arctic on actual sea ice. Later, work consisted of theoretical studies attempting to model the mechanics of penetration (or perforation) and to develop computer coding. Also shaped charges were investigated briefly. Funding limitations prevented actual numerical calculations. There was no validation of the theoretical models with experimental data.

3.2.3 The Sandia ice penetration work was performed later so that the results of the SRI experiments and theoretical studies and the Sandia previous experience in earth penetration investigations were both available as background information. Development and testing in the Arctic of the sea ice penetrometer and the ice penetrating sensor vehicle provided a fund of data concerning in-ice penetration and through-the-ice perforation for 50 to 100 pound vehicles. In the next study an attempt was made to reconcile the ice penetration data with earth penetration and to develop empirical equations for ice penetration. Further test data were used in adjustment and validation of these empirical relationships, first with smaller sized penetrators followed later by larger penetrators and full size bombs. It is recognized that present ice penetration technology strongly depends upon earth penetration technology as its foundation and upon a severely limited number of Arctic tests of ice penetration or perforation. Because of the complexity and costs of tests in the Arctic, penetration tests into gypsite (far more economical) were validated for structural tests simulating the first few feet of Arctic sea ice penetration. The most recent Sandia investigation has begun further development of theoretical modeling of the ice penetration/perforation phenomenon.

3.2.4 The later work by Sandia has been used in this analysis primarily because (a) readily applied empirical relationships were developed, (b) some experimental validation of the relationships has been accomplished with Arctic test data and (c) the sizes and weights of the test devices are more relevant to the problem of sea ice penetration by naval mines.

3.3 RELEVANT FIELD TESTS

3.3.1 The referenced literature contains information and data concerning eight relevant field tests of air-dropped devices. One of these was in the Great Lakes; four were in the Arctic; three were in the ice-simulating gypsite beds of the White Sands Missile Ranges. Table (3-1) lists the tests, their geographical location, the test hardware and the identification of the key documentation applicable to each test.

TABLE 3-1. RELEVANT FIELD TESTS

DATE	LOCATION	TEST HARDWARE	DOCUMENTATION
1. Feb/Mar 1954	Portage Lake, Michigan	3 Mines Mk 25, 4 Mk 36 and 4 Mk 39	Ref (1)
2. Feb 1970	Bay of Port Clarence, Alaska	7 Sea Ice Penetrometers	Ref (6) or App (C) of Ref (13)
3. Apr 1971	Alert, Canada and Thule, Greenland	26 Sea Ice Penetrometers	Ref (7) or App (D) of Ref (13)
4. Apr 1973	Thule, Greenland	7 Ice Penetrating Sensor Vehicles, 10 Ice Penetrators and One Blunt Bottom Mine Shape Scale Model	Ref (9) Ref (13) and Ref (11)
5. Apr 1975	Pt. Barrow, Alaska	7 Mk 82 and One Mk 84 Bomb Shapes 8 Ice Penetrating Sensor Vehicles	Ref (12) Ref (10)
6. Jan 1977	WSMR, NM	3 Mk 82 Bomb Shapes and Two Blunt Bottom Mine Shapes	Ref (17)
7. Aug 1978	WSMR, NM	Five Mk 84 Bomb Shapes	Ref (18)
8. May 1980	WSMR, NM	Four "Soft" Mines	Ref (21)

3.3.2 The present significance of the first through-ice planting of stockpile mines in 1954 is mainly historical. There was no instrumentation and no post-test analysis of hardware function. The important technical information gained then has now been superseded by the knowledge gained from later ice penetration tests.

3.3.3 Of the four ice penetration/perforation tests conducted in the Arctic in 1970-1975, only two involved mine-sized hardware. Penetrators of 925 and 1425 pounds, seven 500 pound bombs and one 2,000 pound bomb made a total of ten test devices heavier than 500 pounds. The costs of Arctic testing always weighed heavily in favor of small test hardware. One blunt bottom mine shape scale model eight inches in diameter (8/21 scale) was tested. No full size mine shapes (as distinguished from bomb shapes) were tested in the Arctic.

3.3.4 The later (1977-1980) structural tests in gypsite at WSMR were all of full size bomb and mine shapes. As previously noted, the gypsite test material was validated for simulating Arctic ice penetration for the first few feet only for structural tests.

3.4 DELIVERY CONSTRAINTS

3.4.1 The most desirable ice impact angle for the mine obviously is at 90° to the horizontal in order to utilize the shortest distance through the ice layer. It would also be expected that maximum thickness of ice perforated and minimum transverse acceleration would be achieved by vertical delivery. In reference (12) critical impact angle was discussed. The critical impact angle is defined as the angle (from horizontal) below which ricochet will occur and above which perforation may occur. Some of the variables which affect this critical angle are: (1) impact velocity, (b) penetrator weight and configuration, (c) nose shape, (d) ice thickness and (e) angle of attack (angle between penetrator centerline axis and its velocity vector). Discussion of delivery parameters and the operational considerations to achieve specific desired impact velocities and impact angles are beyond the scope of this report. It should be noted that in the analyses in this report it is assumed that the impact angle will be 70° or greater from the horizontal.

3.4.2 It should be further noted that Arctic sea ice surfaces (both upper and lower) may at times be flat and smooth, but also may be jumbled masses of huge blocks or chunks of ice presenting extreme variations from the horizontal.

3.5 BASIC ICE PENETRATION EQUATIONS

3.5.1 The early experimental work done by Sandia Laboratories with air dropped sea ice penetrators in the 1970 to 1972 time period (references 6 and 7) led to an assumption of similarity between earth penetration and ice penetration. An extensive terradynamics program at Sandia had led to the development of theoretical and semi-empirical equations describing earth penetration. It was hypothesized that these empirical relationships developed for earth penetration could be used as a starting point for the development of ice penetration relationships.

3.5.2 An experimental program, involving penetrators ranging in weight from 213 pounds (lbs.) to 1425 lbs. and in size from 4.4 inch diameter to 11 inch diameter, was designed and conducted. Introduction of the results of that program together with earlier data led to the modification of the earth penetration relationships, and the development of specific ice penetration empirical equations. Discussion of the test data and the evolution of the empirical equations is found in reference (13). These equations are considered to be the most relevant empirical relationships available to date.

3.5.3 The basic empirical ice penetration relation (from reference (13)) for $V \geq 200$ fps is:

$$D = 2.6 \ (10)^{-3} T_I^{-0.4} N \ (W/A)^{0.6} \ (V-100) \ Ln \ (1+6W^2 \ x \ 10^{-2}) \tag{1}$$

Where:
D = Penetration Depth (See discussion below) (ft)
T_I = Ice Thickness (ft)
N = Nose Coefficient
V = Impact Velocity (fps)
W/A = Weight/Cross Sectional Area (psi)
W = Weight (lbs)
Ln = Natural Logarithm

3.5.4 The term D in the above equation requires some special discussion. It is equal to the penetration depth in ice where the ice thickness (T_I) is significantly greater (2 or more nose lengths) than the value of D. In other words, it represents depth of penetration where perforation does not occur. In order that perforation not occur, it is necessary for the ice thickness to be greater than D by several nose lengths. This is because "spalling" of the lower surface of the ice occurs as the penetrator approaches the ice/water interface. A penetrator approaching within one to two nose lengths will always travel the remaining distance due to the failure of the underside of the ice by "spalling." Where perforation occurs, the value of D together with the value of the path length through the ice (T_p) can be used to calculate the exit velocity (V_E) of the penetrator at the ice/water interface. This equation, from reference (13), is:

$$V_E = V \left[1 - \frac{1}{D_E} (T_p - L/2) \right]^{1/2} \qquad (2)$$

Where: V_E = Exit velocity or velocity at ice/water interface (fps)

V = Impact velocity or velocity at the air/ice interface (fps)

T_p = Path length through ice (ft)

L = Nose length (ft)

D_E = Equivalent D (using equation 1)

3.5.5 In the test situations where perforation by an experimental penetrator occurs, the equivalent depth of penetration (D_E) can be calculated, using the exit velocity, if it is known. This D_E then is an estimate of the maximum thickness which could have been penetrated under the test conditions. The equation for calculating D_E, based on equation (2) is:

$$D_E = V^2 (T_p - L/2)/(V^2 - V_E^2) \qquad (3)$$

The above relationship is useful in comparing a calculated value of D with experimental results where perforation occurs and exit velocity is known. It is used in calculating the equivalent depth of penetration for the experimental data discussed in Section 3.6.

3.6 EXPERIMENTAL VALIDATION OF ICE PENETRATION EQUATIONS

3.6.1 The experimental data available on penetrators having a total weight of at least 200 pounds have been summarized in table 3-2. The data in the table have been summarized from information in references (11), (12), and (13) with the exception of the last three columns, Equivalent Penetration Depth, Computed Penetration Depth, and Error. The Equivalent Penetration Depth was calculated for each test where perforation occurred and exit velocity was measured using equation (3). Computed Penetration Depth was calculated for each test from the known test conditions using equation (1). The error is the percentage difference between the computed depth and either the measured or equivalent depth.

3.7 BASIC ACCELERATION EQUATIONS

3.7.1 Typical plots of deceleration during ice penetration/perforation may be seen in references (11), (12), (13), (22), etc. An idealized plot of deceleration during ice penetration/perforation is reproduced here as figure (3-1).

3.7.2 The shock experienced by a mine during ice penetration/perforation is markedly different from the typical water entry shock signature long familiar to mine designers. Most notable is the sustained high g loading (near peak g) throughout a major portion of the penetration of the ice layer. Obviously, the rate of rise to peak g is related to the nose shape — the deceleration rate of a long pointed nose being slower and a flatter nose more rapid.

3.7.3 The basic equation (from reference (13)) for calculation of average deceleration (a_a) that the penetrator experiences during penetration, when perforation does not occur, is:

$$a_a = \frac{v^2}{2g\,D} \tag{4}$$

When perforation does occur it is:

$$a_a = \frac{v^2 - v_E^2}{2\,g\,T_p} \tag{5}$$

TABLE 3-2. ARCTIC IC
(FOR ITEM

TEST	SER	HARDWARE	WEIGHT (lbs)	DIAMETER (in)	W/A (psi)	NOSE CO-EFFICIENT	NO SHA
APRIL 1973	3	ICE PENETRATOR	221	5.4	9.6	1.0	OG 2.4
	5	ICE PENETRATOR	925	9.0	14.7	1.0	OG 2.4
	9	ICE PENETRATOR	213	4.4	14.2	0.82	OG 1.4
	13	ICE PENETRATOR	213	4.4	14.2	0.56	FL
	16	ICE PENETRATOR	213	4.4	14.2	1.0	OG 2.4
	17	ICE PENETRATOR	213	4.4	14.2	1.0	OG 2.5
		BLUNT BOTTOM MINE SCALE MODEL	360	8.0	7.16	0.8	BL (30°
APRIL 1975	5	Mk 82 BOMB	500	10.8	5.46	1.05	MK
	11	Mk 82 BOMB	500	10.8	5.46	1.05	MK

crh = CALIBER RADIUS HEAD

TABLE 3-2. ARCTIC ICE PENETRATION EXPERIMENTAL TEST DATA
(FOR ITEMS WEIGHING OVER 200 POUNDS)

W/A (psi)	NOSE CO-EFFICIENT	NOSE SHAPE	NOSE LENGTH (ft)	V (fps)	V_E (fps)	T_I (ft)	T_P (ft)	MEASURED PENETRATION DEPTH (ft)	EQUIVALENT PENETRATION DEPTH D_E (ft)	COMPUTED PENETRATION DEPTH D (ft)
9.6	1.0	OGIVE 2.4 crh	1.08	323	180	5.83	5.83		7.7	8.9
14.7	1.0	OGIVE 2.4 crh	1.8	713	668	5.42	5.67		39.0	44.1
14.2	0.82	OGIVE 1.4 crh	.51	260	120	5.75	6.5		7.9	6.6
14.2	0.56	FLAT	0	256	0	5.67		3.5		4.4
14.2	1.0	OGIVE 2.4 crh	.88	229	0	5.67		6.33		6.5
14.2	1.0	OGIVE 2.4 crh	.88	428	350	5.53	6.17		17.3	16.7
7.16	0.8	BLUNT (30° FLAT)	.76	328	120	5.7	6.0		6.5	6.9
5.46	1.05	Mk 82	2.5	486	320	6.2	8.8		13.3	13.5
5.46	1.05	Mk 82	2.5	469		6.2	11.4		>11.4	12.9

TEST DATA

T_I (ft)	T_P (ft)	MEASURED PENETRATION DEPTH (ft)	EQUIVALENT PENETRATION DEPTH D_E (ft)	COMPUTED PENETRATION DEPTH D (ft)	ERROR (%)
5.83	5.83		7.7	8.9	13
5.42	5.67		39.0	44.1	12
5.75	6.5		7.9	6.6	20
5.67		3.5		4.4	20
5.67		6.33		6.5	3
5.53	6.17		17.3	16.7	4
5.7	6.0		6.5	6.9	6
6.2	8.8		13.3	13.5	1
6.2	11.4		>11.4	12.9	
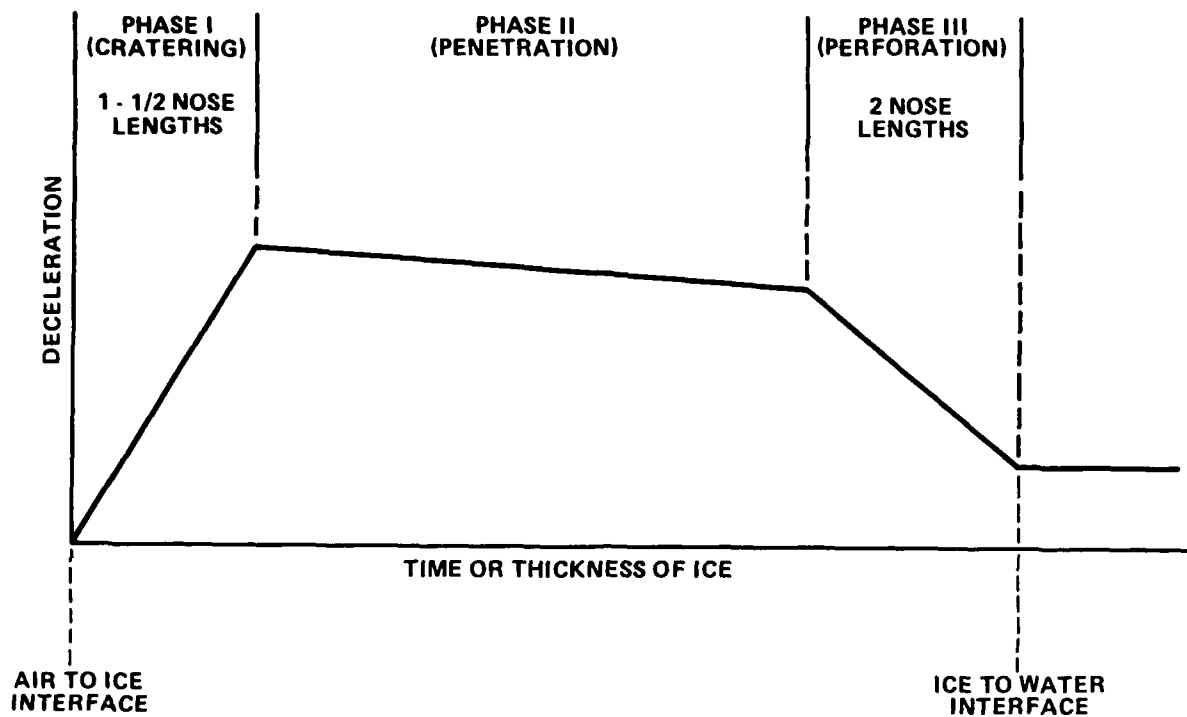
Figure 3-1. Idealized Plot of Deceleration During Ice Penetration/Perforation

In reference (13) the rule-of-thumb empirical equation for estimate of peak acceleration (a_p) is given as:

$$a_p = 1.6 \ a_a \tag{6}$$

thus:

$$a_p = 1.6 \ \frac{(v^2 - v_E^2)}{2g \ T_p} \tag{7}$$

In reference (13), it was stated that insufficient data were available upon which to base an error analysis, but it was estimated that equations (4) and (5) should be accurate within $\pm$ 20% and equation (6) (and thus (7)), should be accurate within $\pm$ 30%.

3.8 EXPERIMENTAL VALIDATION OF PEAK ACCELERATION EQUATION

3.8.1 The experimental data available for penetrators with constant diameter cylindrical shape, only two of which were heavier than 200 pounds, were reexamined to determine the degree of agreement between peak acceleration computed by the above equation and the peak acceleration experimentally measured in the Arctic sea ice penetration tests. The data have been summarized in table 3-3. Again, there is a limited number of usable data points. The available data appear to validate the empirical equation well within the stated accuracy estimate of $\pm$ 30%.

3-10

TABLE 3-3. COMPARISON OF COMPUTED AND MEASURED PEAK g

Test	Ser.	Hardware	V (fps)	V_E (fps)	T_p (ft)	Peak g Comp.	Peak g Meas.	Error %
Feb 70	1	SIP	345	0	5.75	514	450	12
Feb 70	4	SIP	305	0	3.2	722	680	6
Apr 71	B2	SIP	521	0	7.5	899	980	9
Apr 71	B5	SIP	521	0	7.5	899	830	8
Apr 73		Blunt Scale Model	328	100	6.0	404	375	7
Apr 75	5	Mk 82 Bomb	486	320	8.8	378	330	13

3.9 EXPERIMENTAL VALIDATION OF PEAK ACCELERATION EQUATION FOR GYPSITE

3.9.1 In a similar manner, the acceleration data measured in gypsite penetration tests were examined to determine extent of agreement with peak acceleration calculated by use of equation (6). For this comparison the length of path penetrated into the gypsite (T_{PG}) is substituted for D of equation (4). Thus, to calculate peak acceleration for a test in gypsite –

$$a_p = \frac{1.6 \ v^2}{2 \ g \ T_{PG}} \tag{8}$$

3.9.2 The data have been summarized in table 3-4 and, for this limited number of tests, they appear to validate the equation within ± 30%.

TABLE 3-4. COMPARISON OF COMPUTED AND MEASURED PEAK a_p FOR PENETRATION TESTS IN GYPSITE

TEST	SER	HARDWARE	V (fps)	T_{PG} (ft)	COMPUTED a_p	MEASURED a_p	ERROR %
JANUARY 1977	1	Mk 82	500	11	565	500	12
	4	BLUNT BOTTOM MINE	355	4.17	666	750	13
AUGUST 1978	1	Mk 84	454	17	301	250	17
	2	Mk 84	423	15	296	380	28
	3	Mk 84	613	18	518	600	16
	4	Mk 84	650	17	617	600	3
	5	Mk 84	416	12	358	400	12
MAY 1980	1	SOFT MINE	273	6.25	296	350	18
	2	SOFT MINE	277	6.25	305	250	18
	3	SOFT MINE	276	6.67	284	250	12
	4	SOFT MINE	276	6.25	303	300	1

3.10 COMPARISON OF ACCELERATIONS IN ICE AND IN GYPSITE

3.10.1 The test data were examined for instances in which accelerations measured in ice penetration tests may be compared with accelerations measured in gypsite penetration tests. Since there are differences in the actual impact velocities and penetration depths in the tests compared, the following relationship, based on equations (7) and (8) can be used to reconcile the variations in test conditions. A computed peak acceleration value, corrected for velocity and penetration depth variations, can then be compared to the actual measured peak acceleration. Using the proportion

$$\frac{a_p \text{ (ice)}}{a_p \text{ (gypsite)}} = \frac{\dfrac{1.6 \ (v^2 - v_E^2)}{2g \qquad T_p}}{\dfrac{1.6 \ v^2}{2g \quad T_{PG}}}$$

then

$$\text{corrected } a_p(\text{ice}) = \frac{(v^2 - v_E^2) \ (\text{ice})}{T_p \ (\text{ice})} \ \times \ \frac{T_{PG}}{v^2 \ (\text{gypsite})} \ \times \text{ measured } a_p \text{ (gypsite)} \qquad (9)$$

3.10.2 Only two reasonably direct comparisons may be found. Both will be presented here. In the April 1973 ice penetration test of the one-third scale model of the blunt bottom mine (from reference (11)) $V = 328$ fps, $V_E = 100$ fps, $T_p = 6$ ft. and the measured longitudinal peak acceleration was 375 g. In the Jan 1977 Ser. No. 4 gypsite penetration test of the full sized blunt bottom mine (from reference (17)) $V = 355$ fps, $T_{PG} = 4.17$ ft. and the measured $a_p = 750$ g. Using equation (9), a corrected peak acceleration for the gypsite test when the proportional corrections are applied to the measured peak acceleration is found to be 404 g, i.e.

$$\text{corrected } a_p \text{ (gypsite)} = ((328)^2 - (100)^2) \ \times \frac{417}{(355)^2} \ \times 750$$
$$= 404 \ g$$

The corrected 404 g for the gypsite test and the measured 375 g for the ice test are in agreement within 7%. In the same manner, the peak longitudinal accelerations may be compared of the April 1975 Ser. No. 5 ice penetration test of a Mk 82 Bomb and the January 1977 Ser. No. 1 gypsite penetration test of a Mk 82 Bomb. From references (12) and (17), $V = 486$ fps, $V_E = 320$ fps, $T_p = 8.8$ ft, $a_p = 330$ g for the ice test and $V = 500$ fps, $T_{PG} = 11$ ft and $a_p = 500$ g for the gypsite test. A corrected a_p for the gypsite test when the proportional corrections are applied to the measured a_p is 334 g. This computed 334 g compares with the measured 330 g for the ice test within 1%.

3.10.3 These two comparisons indicate very good agreement between longitudinal peak accelerations experienced in gypsite penetration and those experienced in ice penetration. Unfortunately, only two instances of comparison are too few to provide much confidence in the conclusion. Based on these two instances, the indication is that penetration testing in gypsite is a good simulation of penetration testing in Arctic ice for measurement of longitudinal accelerations.

3.11 LATERAL ACCELERATIONS

3.11.1 The transverse acceleration data are summarized in table 3-5. They are too few to permit any substantive conclusions. As can be seen in table 3-5, they may vary from less than to several times greater than the longitudinal acceleration values. Parameters which affect lateral acceleration are angle of attack, impact velocity, impact angle with the ice surface and penetrator nose configuration. Generally, there are no angle of attack data for the ice penetration tests. The importance of angle of attack (angle between the penetrator centerline axis and its velocity vector) is discussed further in Chapter (4).

3.12 BENDING MOMENTS

3.12.1 Very little information has been obtained about the extremely important subject of bending loads on the mine structure during ice penetration. Bending moments were measured in only one penetration test. It was the May 1980 "soft mine" penetration test in gypsite which was a low velocity impact capable of

TABLE 3-5. SUMMARY OF LATERAL ACCELERATION TEST DATA

TEST	SER	HARDWARE	PENETRATION TEST (in)	LONGITUDINAL a_p (g)	LATERAL a_p (g)
APRIL 1975	11	Mk 82 BOMB	ICE	280	$1000^N/1000^B$
	13	Mk 82 BOMB	ICE	380	$1000^N/800^B$
JANUARY 1977	1	Mk 82 BOMB	GYPSITE	500	$>1037^B$
	4	BLUNT BOTTOM MINE	GYPSITE	750	$<50^B$
	5	BLUNT BOTTOM MINE	GYPSITE	—	$<50^B$
AUGUST 1978	1	Mk 84 BOMB	GYPSITE	250	500^B
	2	Mk 84 BOMB	GYPSITE	380	120^B
	3	Mk 84 BOMB	GYPSITE	600	1000^B
	4	Mk 84 BOMB	GYPSITE	600	500^B
	5	Mk 84 BOMB	GYPSITE	400	150^B
MAY 1980	1	SOFT MINE	GYPSITE	350	80^C
	2	SOFT MINE	GYPSITE	250	40^C
	3	SOFT MINE	GYPSITE	250	72^C
	4	SOFT MINE	GYPSITE	300	41^C

LEGEND:

N = LATERAL AXIS ACCELEROMETERS LOCATED IN BOMB NOSE FUSE WELL
B = LATERAL AXIS ACCELEROMETERS LOCATED IN TELEMETRY PACKAGE JUST FORWARD OF AFT BULKHEAD
C = LATERAL AXIS ACCELEROMETERS LOCATED IN TELEMETRY PACKAGE IN NOSE CONE

penetrating about four feet of ice. The complete test report may be found in reference (21). The bending loads measured were between 1.3 and 2.6 million inch pounds. Very mild winds at the time of test provided only a slight angle of attack. The opinion was offered in reference (21) that with 15 knot winds the angle of attack might cause bending loads three times as great as those experienced in the test. There is some, but not conclusive, evidence that in this test the greatest bending loads occurred at about the time of full penetration of the conical nose (one nose length of penetration).

CHAPTER 4
MINE DESIGN CONSIDERATIONS FOR ICE PENETRATION

4.1 MINE DESIGN PARAMETERS AND PENETRATION RELATIONSHIPS

4.1.1 In this chapter the basic empirical equations for ice penetration and impact loading will be applied to certain configuration constraints that are relevant to moored mines of conventional configuration (a buoyant mine case assembly moored by a bottom anchor separated after water entry). The purpose of this parametric study is to determine whether trends exist; favoring, for example, large or small body diameters, etc. Assumptions based on usual mine constraints will be made. The assumptions obviously will not be valid for all possible design concepts but they serve to demonstrate trends and also to exercise the study technique.

4.2 MAXIMUM ICE PERFORATION

4.2.1 The basic empirical penetration relationships, equations (1) and (3), can be used to predict the maximum ice thickness for perforation by applying the following assumptions:

Assuming that the angle of entry will be at least 70° (measured from the horizontal), then:

$$T_p \leq 1.064\ T_I$$

Assuming that $V_E = 0$, then from equation (3):

$$D_E \leq 1.064\ T_I - L/2$$

Assuming that L will always be at least 12 inches and T_I will not exceed 12 feet, then setting $D = D_E = T_I$ is a conservative assumption.

Substituting this assumption in equation (1):

T_M = Maximum Ice Thickness for Perforation

$$T_M = \left[2.6(10)^{-3} \ N(W/A)^{0.6}(V-100) \ Ln \ (1+6W^2 \ x \ 10^{-2}) \right]^{.714} \tag{10}$$

The above empirical equation should be accurate to within $\pm$ 20% based on data in reference (13).

4.2.2 For convenience in performing certain parametric studies the above equations can be separated into the following configuration factors:

$$WA = \text{Weight Area Factor} = \left[2.6(10)^{-3}(W/A)^{0.6} \ Ln \ (1 + 6W^2 \ x \ 10^{-2}) \right]^{.714}$$

$$NF = \text{Noseshape Factor} = N^{.714}$$

The maximum perforation equation becomes:

$$T_M = WA \ x \ NF \ x \ (V-100)^{.714} \tag{11}$$

Since WA and NF are both factors determined by the physical characteristics of the penetrator, then they can be combined, for convenience, into a single factor; Penetration Factor (PF). Then, $T_M = PF \ x \ (V-100)^{.714}$.

4.2.3 In the following paragraphs, the relationships between the above factors and realistic mine design constraints will be discussed. As shown in Paragraph 3.7.3, the peak (and average) deceleration experienced in ice penetration is approximately proportional to the impact velocity squared. In order to maximize perforation capability while minimizing deceleration loads, the WA x NF product should be maintained as large as possible consistent with mine design constraints and maintaining a reasonable payload efficiency.

4.3 WEIGHT AREA FACTOR RELATIONSHIP

4.3.1 In figure 4-1, the relationship between the WA factor and total weight for various diameter penetration vehicles is shown. Several facts are evident from
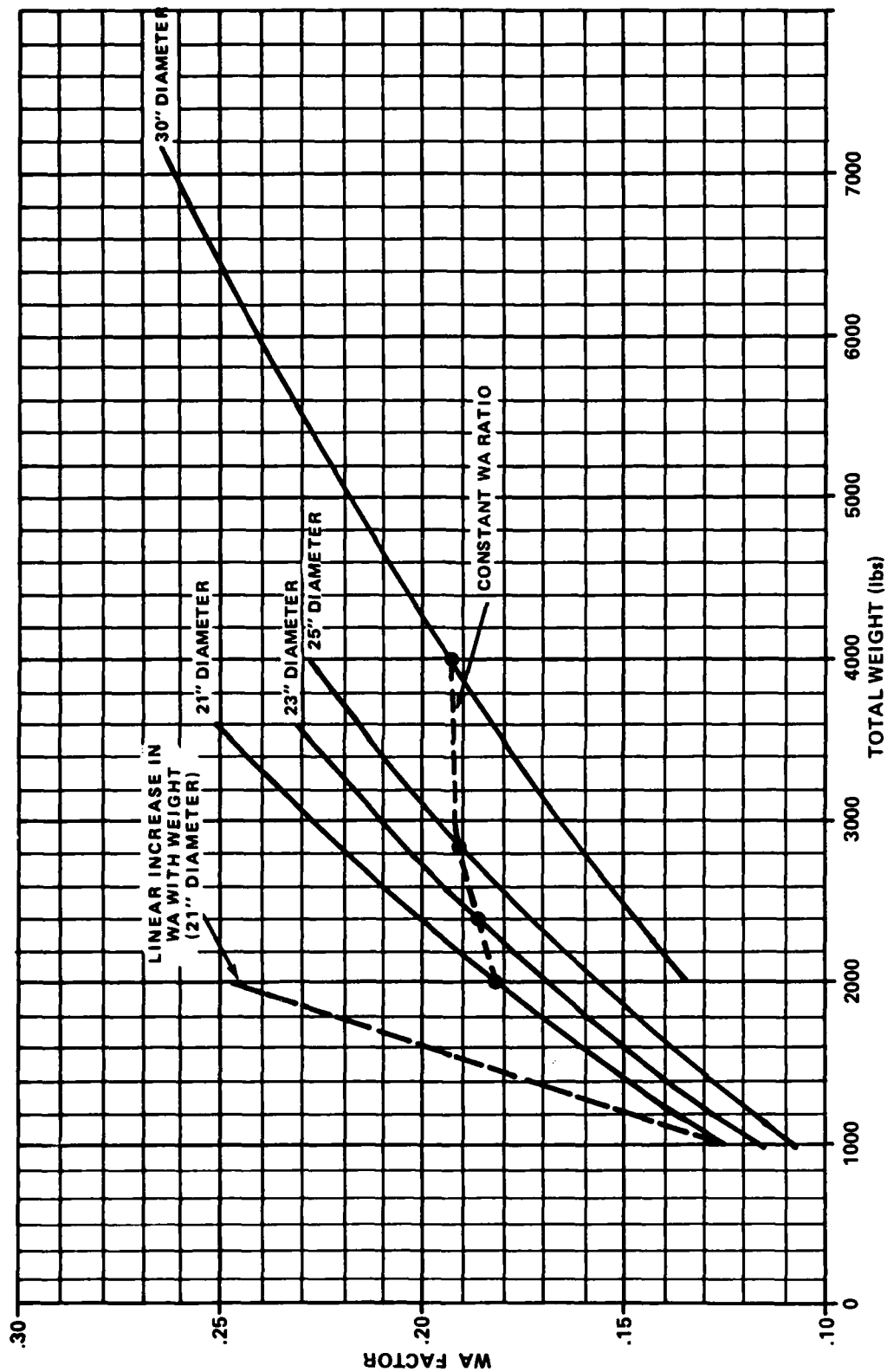
Figure 4-1. WA Factor vs Total Weight

this figure. The first conclusion is that the WA factor increases significantly less than linearly as weight is increased at a given vehicle diameter and density. This is illustrated by the dashed line shown for the 21" diameter vehicle. As the weight for this size vehicle is doubled from 1000 to 2000 pounds, by increasing the vehicle length for example, the WA factor increases only from .124 to .182, an increase of only 47 percent. The second conclusion which can be drawn from figure 4-1 is that the WA factor increases with vehicle diameter as the vehicle density and length are held constant. This is illustrated by the second dashed line on figure 4-1 which shows the result of increasing vehicle diameter from 21 inches to 30 inches. The WA factor increases from .182 to .192, a 5% increase, while the W/A ratio remains constant. The second of the above trends is the more important in the context of usual mine design constraints. This is because the overall vehicle density tends to remain approximately constant as vehicle size is increased and maximum vehicle length is constrained by aircraft interface limitations. This means that using the largest diameter vehicle which can be carried will result in maximizing the ice penetrating potential. This is discussed further in the following sections.

4.4 NOSE SHAPE CONSIDERATIONS

4.4.1 The shape of the nose (penetrator) of an ice penetration vehicle is an extremely important consideration. The values of the nose shape coefficient (N) used in the penetration equation are listed in reference (13). These values are based on terradynamic experiments and, as discussed in Section 3, there is very little experimental validation of the values in ice. However, since there is no theoretical reason or experimental data to refute the assumption that the coefficients are valid in ice, they will be assumed to apply. The value of N (from reference (13)) for the various nose shapes, as well as computed value of $NF = N^{.714}$, are given in table 4-1.

TABLE 4-1. NOSE SHAPE FACTORS

NOSE SHAPE	N	$NF\ (=N^{.714})$
Cone, L/d = 1	.82	.868
Cone, L/d = 2	1.08	1.056
Tangent Ogive, L/d = 1.4	.82	.868
Flat Nose	.56	.661

4.4.2 It is obvious from the above table that the longer the nose taper, the better the penetration, until the length approaches the point of insufficient column strength and becomes unstable. Solid steel cones of length to diameter (L/d) ratio as high as two have been determined to be adequate structurally and have been found to be a good compromise between penetration and structural considerations. However, in the case of mines, there are additional considerations resulting from overall length constraints and buoyancy requirements. The impact of these factors in achieving an optimum compromise of penetration capability and payload is discussed in the following sections.

4.5 PAYLOAD/PENETRATION RELATIONSHIP FOR MOORED MINES

4.5.1 In the design of moored mines, there is the obvious requirement that the mine case assembly, after the anchor and other discardable parts are separated, must be buoyant by an adequate amount to insure maintenance of acceptable depth stability under the projected conditions of bottom depth and current velocity. The buoyancy requirements can vary from 50 to several hundred pounds depending on the operating requirements and conditions. A buoyancy margin of 100 pounds is a reasonable average value and will be used in the following discussion and calculations. The maximum mine length and weight are determined by aircraft compatibility considerations and may vary considerably. Weight and length limitations of 2200 pounds and 120 inches respectively are conservative values and will be used in the following discussion.

4.5.2 With the assumed length limitation, a moored mine in the diameter range of interest will not be buoyant at the desired total weight. It is therefore assumed that the mine must consist basically of two major components, a "separable" essentially solid, nose section and the "payload" or main body section. The nose section will be assumed conical. The separation line may lie anywhere within the conical section or the cylindrical body section. The separable nose may serve partially or completely as an anchor. The separable section is assumed to be steel having a density of .283 pounds per cubic inch. In reality this section may contain functional components required for mooring which would tend to reduce this assumed density. However, some material having a density higher than steel may be used in the nose section, thus bringing the overall density up to the assumed

4-5

value. The payload section, which remains after the nose is discarded, is assumed to have a positive buoyancy in sea water of 100 pounds. The assumed configuration and definition of variables is shown in figure 4-2. The equations shown in figure 4-2 permit calculating a separation line which will result in the desired value of total weight (W) while maintaining the required minimum positive buoyancy (BU) of the payload section.

4.5.3 The equations and relationships in figure 4-2 can be used to determine certain relationships between diameter, nose length and penetration capability. With a given nose shape and body diameter, penetration capability can be increased only by increasing the total weight of the penetrator. Assuming an overall length constraint, total weight is increased by allowing the separable solid nose section to utilize a greater proportion of the allowable body length. This reduces the length of the resultant payload and therefore the "efficiency" of the weapon. Alternately, penetration capability can be increased by lengthening the taper of the nose. If a nose taper of $L/d = 2.0$ rather than $L/d = 1.0$ is assumed, then an entirely new set of total weight versus separation point values will apply. One of the objectives of the parametric study is to determine whether an L/d nose taper of 2.0 is more efficient in terms of payload than a more blunt nose of L/d of 1.0 for example. Similarily, the penetration capabilities of different body diameters can be parametrically investigated to assess the benefits of using a larger diameter.

4.5.4 The general procedures followed in examining the effect of nose shape and body diameter are as follows:

1. A desired value of the product ($WA \times NF$) is assumed together with an assumed nose shape and body diameter.

2. The assumed nose shape determines the value of NF and the required value of WA can therefore be calculated.

3. Using the required value of WA and the assumed body diameter, the required total weight is determined from figure 4-1.

FOR L1 < L2
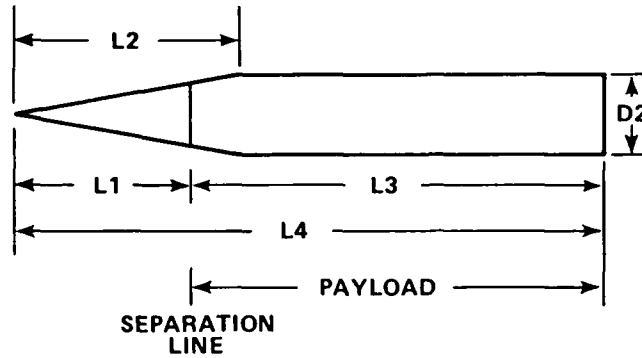
LEGEND:

d1 = DENSITY OF PENETRATOR = .283 LBS / CU.IN.

d(WATER) = .0364 LBS/CU.IN.

BU = BUOYANCY REQUIRED (LBS)

$A = AREA = \pi(D2)^2/4$

W = DESIRED TOTAL WEIGHT (LBS)

$$L1 = \left[(W - A(L4 - 2L2/3)(.0364) + BU)\,3L2^2/A(d1 - .0364)\right]^{1/3}$$

$W1 = A(L1)^3\, d1/3(L2)^2 =$ WEIGHT OF SEPARABLE SECTION

PAYLOAD = W − W1

FOR L1 > L2
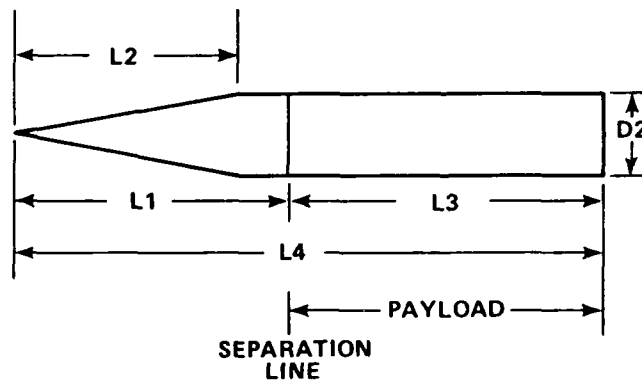
L1 = (W + Ad1(2(L2)/3) − AL4(.0364) + BU)/A(d1 − .0364)

W1 = Ad1 (L1 − 2(L2)/3) = WEIGHT OF SEPARABLE SECTION

PAYLOAD = W − W1

Figure 4-2. Assumed Mine Configuration

4. Using the required total weight, assumed body diameter, and assumed nose shape, the length of the separable nose section and the resultant payload weight can be calculated using the relationships shown in figure 4-2.

The above calculations have been performed for Penetration Factors (WA x NF) ranging from .10 to .20, for conical nose configurations of L/d = 2.0 and L/d = 1.0, and for body diameters of 21 inches, 23 inches, and 25 inches. These results are shown in table 4-2 and figures 4-3 and 4-4. The two conical nose shapes were chosen since they likely represent the extreme situations. An ogival nose which could also be a viable concept would lie between the two cone configurations chosen.

4.6 PARAMETRIC STUDY RESULTS

4.6.1 Figure 4-3 graphically illustrates the results of the parametric data tabulated in table 4-2. It should be noted that the term "payload" referred to in the tables and in the following discussion refers to the weight of the buoyant mine assembly remaining after the separable nose section has been discarded. The true payload in terms of actual explosive weight would be determined by the structural efficiency of the mine assembly. The term weight efficiency refers to the ratio of payload weight to total weight of the configuration. It can be seen from figure 4-3 that the curves for a nose cone taper of L/d = 2.0 consistently result in a weight efficiency approximately 10 to 12 percent higher than with a L/d ratio of 1.0 for a given Penetration Factor. The curves also show that there is not much change in weight efficiency between body diameters of 21 inches to 25 inches. There is, however, a total weight constraint on the system. This is assumed to be 2200 pounds and is shown by the "+" on each of the curves and the curves are shown dashed beyond this weight limitation. This weight limitation does not change the advantage in weight efficiency that is gained in using a nose taper ratio of L/d = 2. It does, however, limit the extent to which weight efficiency can be traded off to obtain a higher Penetration Factor. Figure 4-3 clearly shows the advantage of the L/d = 2 conical nose from a weight efficiency standpoint.

TABLE 4-2. WEIGHT - PAYLOAD - PENETRATION FACTOR

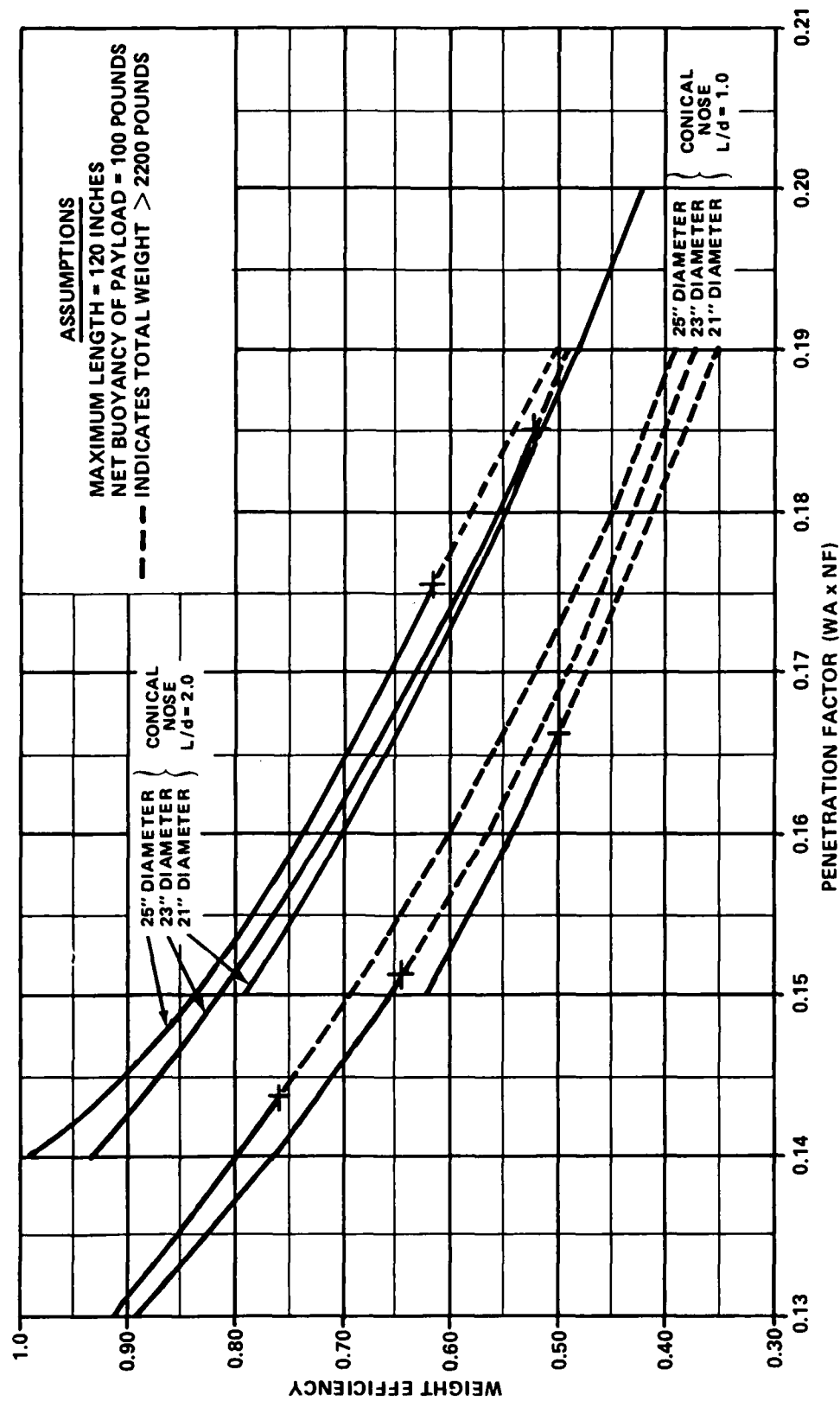| DIA (INCHES)	PENETRATION FACTOR (WAxNF)	NOSE CONFIG	NOSE LENGTH (INCHES)	NOSE FACTOR (NF)	REQD WA FACTOR (LBS)	REQD TOTAL WT (LBS)	PAYLOAD (LBS)	DISCARD LENGTH (INCHES) L1	WEIGHT EFF
21	0.20	CONE L/d = 2	42	1.056	0.190	2180	908.8	40.9	0.42
	0.19				0.180	1950	940.0	37.9	0.48
	0.18				0.170	1750	966.0	34.8	0.55
	0.17				0.161	1600	987.0	32.1	0.62
	0.16				0.151	1450	1006.0	28.8	0.69
	0.15				0.142	1300	1027.0	24.5	0.79
	0.14				0.133				
	0.13				0.124				
	0.12				0.114				
	0.11				0.104				
	0.10				0.095				
21	0.20	CONE L/d = 1	21	0.868	0.230				
	0.19				0.219	2800	1006.0	32.3	0.35
	0.18				0.207	2550	1043.0	29.4	0.41
	0.17				0.196	2300	1080.0	26.4	0.47
	0.16				0.184	2050	1117.0	23.5	0.54
	0.15				0.173	1850	1146.0	21.2	0.62
	0.14				0.161				
	0.13				0.150				
	0.12				0.138				
	0.11				0.127				
	0.10				0.115				
23	0.20	CONE L/d = 2	46	1.056	0.190	2500	1083.7	42.45	0.43
	0.19				0.180	2300	1109.0	40.05	0.48
	0.18				0.170	2080	1139.0	37.04	0.55
	0.17				0.161	1850	1170.0	33.2	0.63
	0.16				0.151	1650	1197.0	29.0	0.72
	0.15				0.142	1500	1217.0	24.8	0.81
	0.14				0.133	1330	1240.0	16.9	0.93
	0.13				0.123	1150			
	0.12				0.114				
	0.11				0.104				
	0.10				0.095				
23	0.20	CONE L/d = 1	23	0.868	0.230	4000	1112.0	39.88	
	0.19				0.219	3250	1222.0	32.56	0.37
	0.18				0.207	2950	1267.0	29.6	0.43
	0.17				0.196	2650	1311.0	26.7	0.49
	0.16				0.184	2400	1348.0	24.3	0.56
	0.15				0.173	2150	1391.0	21.7	0.65
	0.14				0.160	1870	1430.0	18.1	0.76
	0.13				0.150	1640	1461.0	13.4	0.89
	0 12				0.138	1400			
	0.11				0.127	1200			
	0.10				0.115	1000			
25	0.20	CONE L/d = 2	50	1.056	0.190				
	0.19				0.180	2600	1293.0	41.3	0.50
	0.18				0.170	2300	1333.0	37.4	0.58
	0.17				0.161	2100	1360.0	34.2	0.65
	0.16				0.151	1900	1387.0	30.2	0.73
	0.15				0.142	1700	1414.0	24.9	0.83
	0.14				0.133	1450	1448.0	4.5	0.99
	0.13				0.123				
	0.12				0.114				
	0.11				0.104				
	0.10				0.095				
25	0.20	CONE L/d = 1	25	0.868	0.230				
	0.19				0.219	3700	1458.0	32.8	0.39
	0.18				0.207	3350	1509.0	29.9	0.45
	0.17				0.196	3000	1561.0	27.0	0.52
	0.16				0.184	2700	1616.0	24.5	0.60
	0.15				0.173	2400	1656.0	21.56	0.69
	0.14				0.161	2100	1697.0	17.6	0.81
	0.13				0.150	1900	1725.0	13.3	0.91
	0.12				0.138				
	0.11				0.127				
	0.10				0.115				

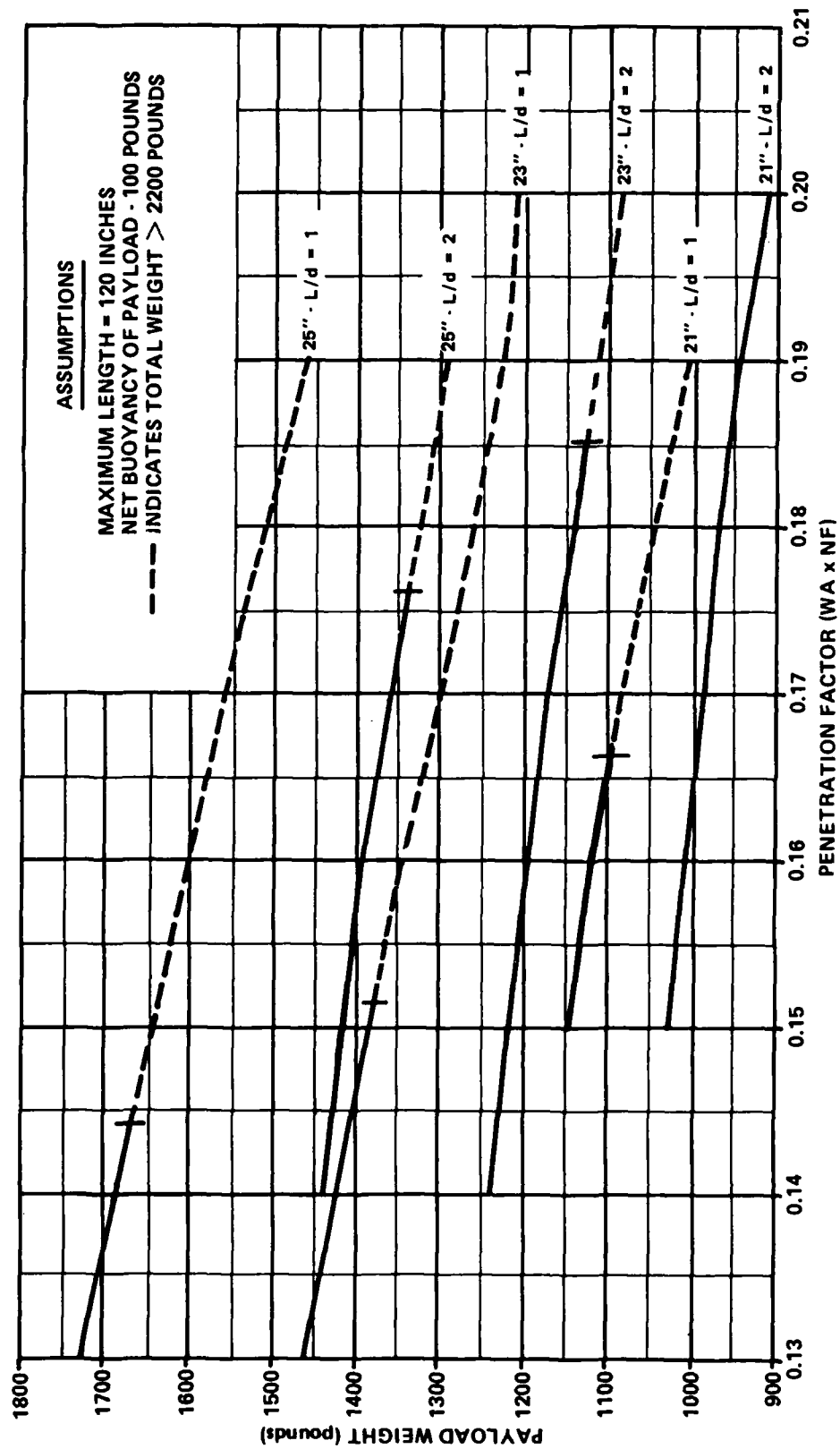Figure 4-3. Penetration Factor vs Weight Efficiency

4-10

Figure 4-4. Penetration Factor vs Payload Weight

4-11

4.6.2 Figure 4-4 illustrates the relationship between absolute value of payload weight and Penetration Factor. The point on each of the curves representing total weight of 2200 pounds is again shown by a "+" and the curves are shown dashed for total weights greater than 2200 pounds. This figure clearly shows the advantage of the larger diameter in permitting a greater absolute value of payload. The figure also illustrates the limitations in trading off payload weight to obtain greater penetration capability. For example, if a Penetration Factor of .18 is desired, a 25 inch body diameter cannot be used since the total weight would exceed 2200 pounds, as would 21 inch and 23 inch diameter bodies with a nose taper ratio of 1.0. The only viable configurations would be a 21 inch diameter with a nose taper ratio of 2.0 and a 23 inch diameter, also with a nose taper ratio of 2.0. The 23 inch diameter body would, of course, be a better choice since the payload capability is significantly greater.

4.7 LONGITUDINAL SHOCK LOADING

4.7.1 The empirical relationship from reference (13) for maximum deceleration as a function of impact velocity was discussed in Section 3. This relationship is:

$$a\ (\text{max}) = 1.6\ (V^2 - V_E^2)/2g\ T_p$$

Where V = Impact velocity (fps)

V_E = Exit velocity (fps)

g = Gravitational constant = 32.2 feet per sec^2

T_p = Path length (ft)

Assuming that we are looking for the minimum velocity to achieve perforation, then V_E can be assumed to be zero. Assuming that the ice impact angle will be at least 70° from the horizontal, then $T_p = 1.064\ T_M$. The above equation then reduces to:

$$a\ (\text{max}) = .0233\ V^2\ T_M$$

Where T_M = Thickness of ice

From equation (10):

$$T_M = WA \times NF \times (V-100)^{.714}$$

If Penetration Factor (PF) = WA x NF

$$T_M = PF \ (V-100)^{.714}$$

Combining with above:

$$a \ (max) = 0.233 \ [\frac{T_M}{PF} + 100]^2/T_M$$

This relationship is shown graphically in figure 4-5.

4.8 TRANSVERSE ACCELERATION AND BENDING

4.8.1 A transverse force can exist on the nose of the mine entering ice as a result of two factors. First, the resisting force of the ice may be assymetrical as a result of a very large impact angle (θ). This is shown in the following sketch:
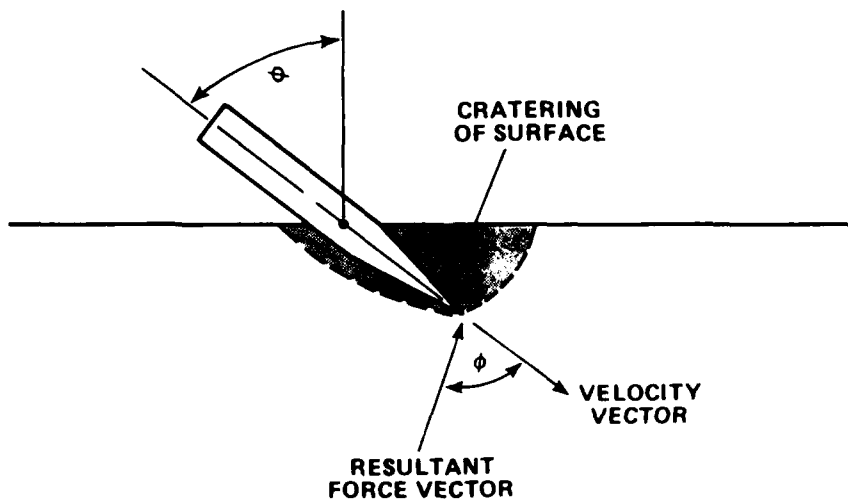
Figure 4-5. Maximum Thickness vs Acceleration Loading

4-14

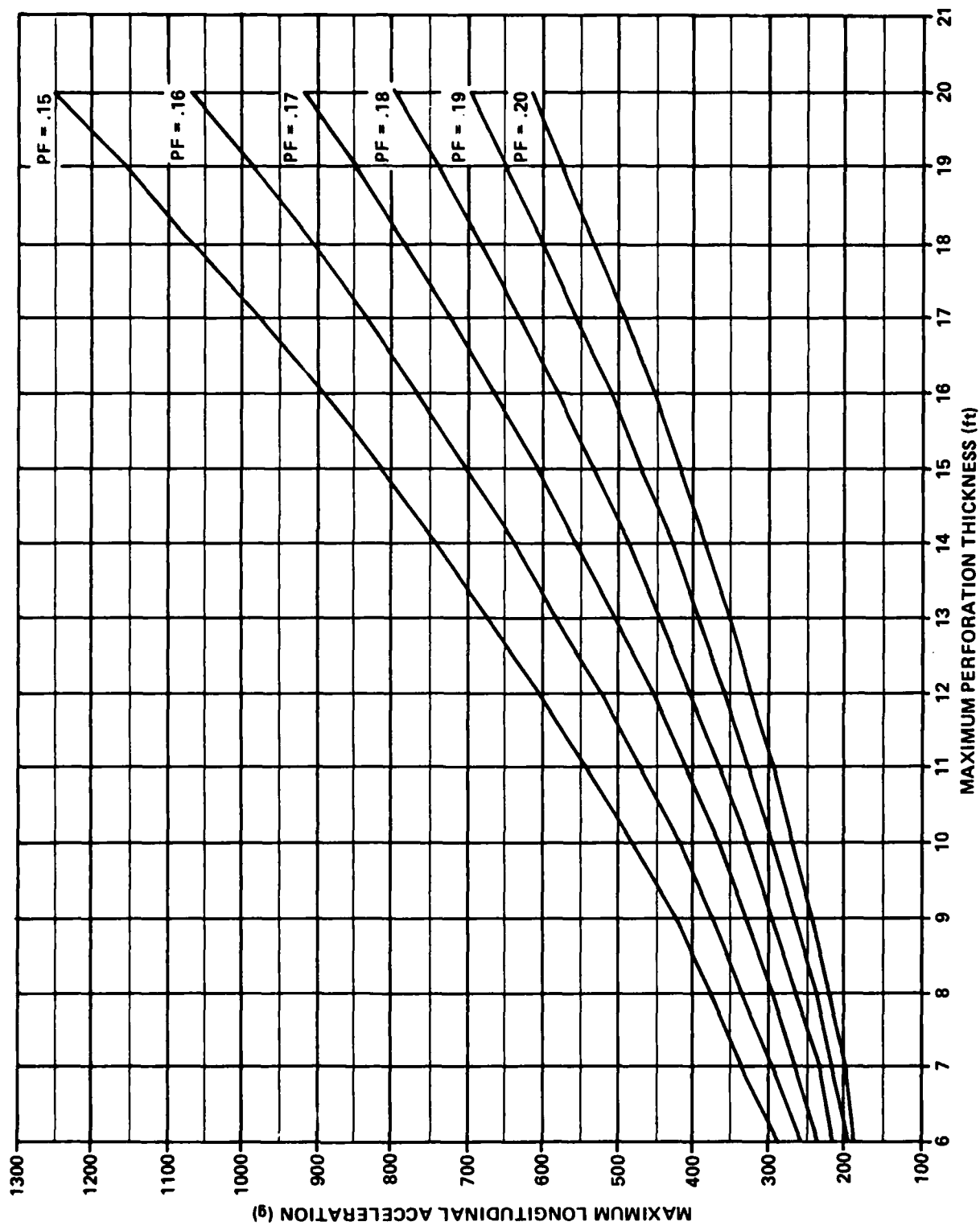The resultant force vector is at some angle (ϕ) with respect to the longitudinal axis of the body due to cratering of the ice surface and resulting asymmetrical force response. This is the phenomenon that results in broaching since the transverse force will cause the mine to follow a curved path. If the curvature is great enough that the asymmetry persists, then broaching will occur. This asymmetrical behavior of the ice is probably not a factor except at impact angles (θ) greater than 20 to 30 degrees. The second source of transverse force on the nose results from the effective transverse velocity occurring when the mine impacts with an angle of attack (α). This is shown in the following sketch:
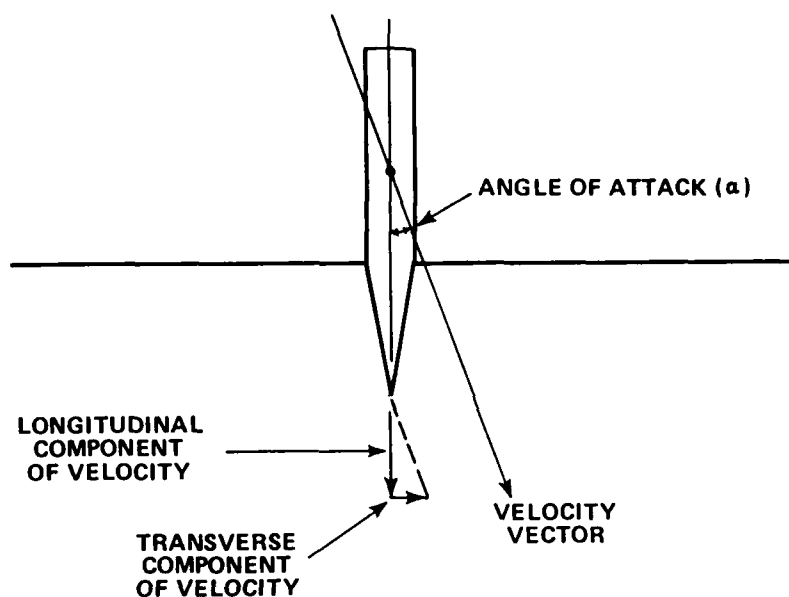
The angle σ between the longitudinal axis of the body and the direction of the impact vector results in transverse and longitudinal components of velocity. The longitudinal component produces the expected value of longitudinal deceleration. The transverse velocity component will produce a transverse force of significant magnitude. The actual magnitude of this transverse force will be dependent upon the nose shape and the nature of the material being penetrated. Experimental data have shown transverse acceleration values of two or more times the longitudinal acceleration which is indicative of relatively large transverse forces. The

transverse acceleration loads on components are probably not a major cause for concern since they are of relatively short duration (5 milliseconds at the most), but the resultant bending loads may be a problem as shown in the following example:

Assume a mine 120 inches long, weighing 2200 pounds distributed approximately uniformly. The centroid will be located at the mid-length and the value of radius of gyration squared (k^2) will be assumed to be 10 ft.^{2}.

Assume a transverse acceleration of 500 g is measured at a point 30" forward of the centroid.

The transverse force required to produce this acceleration can be calculated as follows:

$$F_T = A_T \times M / \left[\frac{RL}{2k^2} + 1 \right]$$

F_T = Transverse force (lb)

A_T = Transverse acceleration = 500 g

M = Mass = 2200 lb

R = Radius to accelerometer measurement = 2.5 ft

L = Length of body = 10 ft

k^2 = 10 ft^2

$$F_T = (500)(2200) / \left[\frac{(2.5)(10)}{(2)(10)} + 1 \right] = .488 \times 10^6 \text{ lb}$$

The maximum bending moment will occur at a distance of approximately L/4 back from the end of the nose and will be approximately equal to .180 $F_T L$.

Maximum Bending Moment = (.180)(.488)(10^6)(120)

= 10.5 $\times 10^6$ in lb

Asuming a .5 inch thick wall (21 inches diameter), the section modulus will be 168.2 inches^3. The bending stress will be:

Bending Stress = $10.5 \times 10^6/168.2$ = 62,400 psi

This stress would be combined with the compressive stresses in the case wall resulting from the axial deceleration force. Assuming a value of axial deceleration of 350 g the axial compressive stress on the assumed .5 inch thick wall would be approximately 17,500 psi. The above illustration indicates that the bending load can result in a very significant additional stress imposed on a structure designed primarily for the compressive stresses associated with axial deceleration. The stress level in the example could be tolerated by increasing the wall thickness, depending on the case material. However, accommodating this bending load can impose additional design constraints even at the modest level of transverse loading assumed in the example. The necessity for designing the system to minimize the transverse forces and resultant bending loads on the structure is obvious from the example.

CHAPTER 5
SUMMARY AND CONCLUSIONS

5.1 LITERATURE REVIEW

5.1.1 Review of the literature reveals that there was interest in the subject of
ice penetration by naval mines as early as 1952 and that it has continued. The
relevant literature has been referenced in this report and Appendix (A) is a
complete list with a brief description of the content of each document.

5.1.2 Early investigation of ice penetration was largely by laboratory experiments
and theoretical studies. Extensive investigations and tests of earth penetration
of weapons in approximately the same time period provided a fund of information
concerning earth penetration technology. Feasibility and preliminary development
tests in the Arctic of Sea Ice Penetrometers and Ice Penetrating Sensor Vehicles
provided valuable Arctic sea ice penetration information and data for 50 to 100
pound vehicles. In fiscal year 1973 mine sized penetrator tests were made in
Arctic sea ice and ice penetration data were used in a study of the application of
earth penetration technology to ice penetration technology. Modified empirical
equations were developed for prediction of ice penetration, average longitudinal
acceleration and peak longitudinal acceleration. Only four penetration tests have
been conducted by instrumented air-dropped vehicles in Arctic sea ice. Only two of
these included mine-sized penetrators and bomb cases. No full-sized mine
structures larger than bomb shapes have been tested in Arctic sea ice penetration
tests. Because of the limited number of ice penetration tests the ice penetration
technology which has been developed has depended as much as possible on earth
penetration technology for its foundation. Because the difficulty, complexity and
cost of Arctic testing resulted in very slow accumulation of data, penetration
testing in gypsite simulating structural testing in Arctic sea ice was begun. Full

sized bomb cases, blunt bottom mine case shapes and test vehicles simulating moored mine structures were subjected to penetration tests in gypsite to obtain additional penetration, shock and structural loading information.

5.2 VALIDATION OF ICE PENETRATION RELATIONSHIPS

5.2.1 Reference (13) provides the basic empirical equation for prediction of depth of ice penetration (D) when perforation does not occur (equation (1), Paragraph 3.5.3) and an equation (equation (2), Paragraph 3.5.4) for calculation of exit velocity (V_E) when perforation does occur. For the test situation in which perforation occurred, an equivalent depth (D_E) can be calculated (equation (3), Paragraph 3.5.5) which is an estimate of the maximum depth which could have been penetrated under test conditions. Test data are available for nine relevant (penetrator weight greater than 200 pounds) tests in Arctic sea ice. To perform an experimental validation of the empirical equations, the Computed Penetration Depth (D) was calculated for each of the nine tests and compared to either the calculated Equivalent Penetration Depth (D_E) or the measured depth. The difference was within 20% in all instances.

5.2.2 Reference (13) also provides an empirical equation (equation (7), Paragraph 3.7.3) for estimate of peak longitudinal acceleration (a_p). For the six relevant tests in Arctic sea ice (penetrator weighed over 200 pounds in only two) the comparison of computed and measured peak g appear to validate the empirical equation well within the stated accuracy estimate of $\pm$ 30%.

5.2.3 Lateral acceleration data exist for only two tests in Arctic sea ice and without concurrent angle of attack data. They are too few to form any substantial conclusions but the data suggest that lateral accelerations may be several times the value of longitudinal accelerations.

5.3 COMPARISON OF ACCELERATIONS IN ICE AND GYPSITE

5.3.1 Two reasonably direct comparisons may be found for comparison of longitudinal accelerations in ice penetration tests and gypsite penetration tests. For these two instances, a corrected peak acceleration for the gypsite test (equation (9), Paragraph 3.10.1) is found to be in good agreement with the measured

peak acceleration for the ice test thus indicating that, for measurement of longitudinal accelerations, penetration testing in gypsite is a good simulation of penetration testing in Arctic sea ice. Unfortunately, only two instances of comparisons are too few to provide much confidence in the conclusion.

5.3.2 The available data are too sparse to permit any meaningful comparison of lateral accelerations encountered in ice penetration tests and gypsite penetration tests.

5.4 MINE DESIGN CONSIDERATIONS

5.4.1 The empirical ice penetration equations developed by Sandia Corporation (reference (13)) provide a method for predicting the thickness of ice that can be perforated by a given weapon configuration under given impact conditions. Analysis of various elements of the equations permits developing certain criteria and parametric relationships which can aid in mine design. The nose (penetration) configuration, weight, and weight to cross section area ratio are the important design parameters. Parametric studies, recognizing the conventional constraints in mine design of total weight, overall length, and diameter, indicate that the maximum combination of payload weight and penetration capability is achieved by using a 23 inch diameter body with a nose taper of $L/d = 2$. A larger diameter body (25 inches) permits larger payloads but exceeds the assumed overall weight limitation of 2200 pounds at the higher (and probably necessary) levels of penetration capability.

5.4.2 The parametric studies show that a useful range of thickness of ice perforation is attainable within a reasonable range of longitudinal acceleration values while maintaining a reasonable ratio of payload (buoyant mine structure remaining after discarding penetrator nose) to total weight. For example, a 23 inch diameter mine with a payload weight of approximately 1130 pounds (total weight of approximately 2020 pounds) should be capable of penetrating 8 feet of ice at an acceleration level of 260 g and 12 feet of ice at 400 g.

5.4.3 The data available suggest that the problem of surviving transverse loads may be far more severe than surviving the longitudinal deceleration forces. Supporting data are very minimal but there is strong evidence that the transverse

forces at the nose increase quite rapidly if there is a transverse velocity vector. Calculations show that a transverse load producing an acceleration level in the order of 500 g could produce bending stress in the case wall of 3 to 4 times that produced by the longitudinal deceleration. The significance of transverse loads indicates that design methodology which will minimize the transverse loads will have to be adopted. This will probably require the development of retardation techniques and body configurations which will minimize the angle of attack at impact. In addition case wall design and joint locations will need to recognize the existence of bending loads of significant magnitude and the manner in which these loads vary along the case length.

5.5 CONCLUSIONS

5.5.1 Analysis of the degree of validation of the empirical equations by field testing in ice shows good agreement but the extent of supporting data is, in many cases, very limited. This is particularly true in the case of sizes and weights relevant to mine design. The sparsity of data is understandable in view of the high cost of conducting actual ice penetration field tests, especially with the larger size shapes. Data is particularly limited on transverse forces (accelerations) and the effect of angle of attack, nose shape and ice characteristics on the forces generated.

5.5.2 Development and validation of simulation of at least the initial ice entry phase needs to be accomplished. Early in the development of the present family of water entry mines, it was found that good laboratory methods of simulating the water entry phenomena were essential in developing components and structures. The same requirement and benefits will exist for simulating ice entry. Unfortunately, the characteristics of the entry are so dissimilar to water that the water entry simulation methods are probably of limited usefulness. The development of the gypsite testing technique is a step in this direction in that full scale drops onto gypsite can be accomplished at significantly less cost than drops onto ice. The accuracy of the simulation of longitudinal forces (accelerations) has been validated to a certain extent. However, the degree of simulation of transverse levels cannot be determined until more reference data on actual behavior in ice is obtained. Some consideration should be given to the development of ice entry testing that would be more economical and more controllable than the air drops into

gypsite. In other words, a technique more nearly approaching laboratory testing methods is required. The methods used in terradynamics investigations of propelling the test specimen into a medium such as soil may be useful.

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1. J. R. Blouin, "Project Ice Cube; aircraft drops on," NOL TN 2594, U.S. Naval Ordnance Laboratory, 6 April 1954, CONFIDENTIAL.

2. Bernard Ross, "Penetration Studies of Ice with Application to Arctic and Subarctic Warfare," 174482, Stanford Research Institute, Menlo Park, California, November 1965, UNCLASSIFIED.

3. Bernard Ross, "Penetration Studies of Ice with Application to Arctic and Subarctic Warfare," SRI-NWRC-3072, Stanford Research Institute, Menlo Park, California, May 1967, UNCLASSIFIED.

4. Bernard Ross and Sathya Hanagud, "Penetration Studies of Ice with Application to Arctic and Subarctic Warfare," SRI-NWRC-452-4, Stanford Research Institute Menlo Park, California, September 1969, UNCLASSIFIED.

5. Bernard Ross, Sathya Hanagud, Gursharan Sidha, "Penetration Studies of Ice with Application to Arctic and Subarctic Warfare," SRI-NWRC-7000-452-5, Stanford Research Institute, Menlo Park, California, April 1971, UNCLASSIFIED.

6. C. W. Young and J. L. Kiker, "The Development of a Sea Ice Penetrometer," SC-DR-70-483, Sandia National Laboratories, Albuquerque, NM, August 1970, UNCLASSIFIED.

7. C. W. Young and L. J. Keck, "An Air-Dropped Sea Ice Penetrometer," SC-DR-71-0729, Sandia National Laboratories, Albuquerque, NM, December 1971, UNCLASSIFIED.

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9. C. W. Young, "Development of an Ice Sonobuoy Penetrator" (U), SLA-73-0754,
    Sandia National Laboratories, Albuquerque, NM, December 1973, CONFIDENTIAL.

10. C. Wayne Young and Louis V. Feltz, "Arctic Tests of Ice Penetrating Sensor
    Vehicles" (U), SAND 76-0113, Sandia Laboratories, Albuquerque, NM, June 1976,
    CONFIDENTIAL.

11. Sandia Laboratories (C. Wayne Young) letter of July 27, 1973 to Naval Ordnance
    Laboratory (Mr. M. M. Kleinerman), "Final Report on Ice Penetration Test of
    QUICKSTRIKE Configuration," UNCLASSIFIED.

12. C. Wayne Young, "Sea Ice Penetration by Mk 82 and Mk 84 Bomb Shapes" (U),
    SAND 75-0641, Sandia Laboratories, Albuquerque, NM, April 1976, CONFIDENTIAL.

13. C. W. Young, "Penetration of Sea Ice by Air-Dropped Projectiles" (U),
    SLA-74-0022, Sandia Laboratories, Albuquerque, NM, March 1974, CONFIDENTIAL.

14. Sandia Laboratories (C. Wayne Young) letter M1762 of June 14, 1974 to Naval
    Ordnance Laboratory (Mr. M. M. Kleinerman), CONFIDENTIAL.

15. Sandia Laboratories (C. Wayne Young) letter MO3645 of July 11, 1974 to Naval
    Ordnance Laboratory (Mr. M. M. Kleinerman), CONFIDENTIAL.

REFERENCES (Cont.)

16. Sandia Laboratories (C. Wayne Young) letter of January 2, 1973 to Naval
    Ordnance Laboratory (Mr. M. M. Kleinerman), "Status Report on Ice Penetration
    Studies," UNCLASSIFIED.

17. Sandia Laboratories (C. Wayne Young) letter of March 7, 1977 to Naval Surface
    Weapons Center (Mr. M. M. Kleinerman), UNCLASSIFIED.

18. Sandia Laboratories (C. Wayne Young) letter of August 31, 1978 to Naval
    Surface Weapons Center (Mr. M. M. Kleinerman), "QUICKSTRIKE Tests at White
    Sands Missile Range (WSMR)," UNCLASSIFIED.

19. Sandia Laboratories (C. Wayne Young) letter of May 31, 1979 to Naval Surface
    Weapons Center (Robert Detwiler), UNCLASSIFIED.

20. Naval Surface Weapons Center U13:SW:mit letter 8550 Ser 2369 of 21 June 1979
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    UNCLASSIFIED.

21. Sandia Laboratories (C. Wayne Young) letter of July 23, 1980 to Naval Surface
    Weapons Center (Mr. M. M. Kleinerman), UNCLASSIFIED.

22. M. Michael Hightower, Frederick R. Norwood, C. Wayne Young, "Development of an
    Ice Penetration Model," SAND 82-0599, Sandia National Laboratories,
    Albuquerque, NM, December 1982, UNCLASSIFIED.

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23. A. H. Peale, "Proceedings of the Conference on the Naval Minefield (14th):
    Ice Cover," NOL TR 71-71 (U), Naval Ordnance Laboratory, White Oak, Maryland,
    April 1971, SECRET.

24. J. M. Jones, "The Design of a Large Shaped Charge Suitable for the Perforation
    of Arctic Sea-Ice," Defense Research Establishment, Valcartier, Quebec,
    Canada, May 1971, UNCLASSIFIED.

25. Warren H. McInteer, "Arctic Mining Capabilities and Requirements (U),"
    NSWC TR 79-323 and ONR TR 79-131, Naval Surface Weapons Center, Silver Spring,
    Maryland, August 1979, SECRET.

26. Glenn L. Matteson, "SUBROC Depth Bomb, Ice Penetration of (U)," Naval Surface
    Weapons Center internal memorandum from U23 to U32, 17 June 1982, CONFIDENTIAL.

APPENDIX A

RESUME OF RELEVANT LITERATURE

APPENDIX A

RESUME OF RELEVANT LITERATURE

A.1 Reports and data relevant to investigations and tests of ice penetration by mines (or similar ice penetrators) are listed below: Also, a brief description of the document content is presented.

1.   NOLTN-2594

     Naval Ordnance Laboratory

     Project ICE CUBE; Aircraft drops on

     J. R. Blouin

     6 April 1954

     CONFIDENTIAL

     In February/March 1954 seven parachute retarded mines Mk 25 and Mk 36 plus four free-fall mines Mk 39 were planted through 16 to 24 inch thick ice into Portage Lake, Michigan. This was the first known test of aircraft planting of mines through ice.

2.   U-174482

     Stanford Research Institute, Menlo Park, California

     Penetration Studies of Ice with Application to Arctic and Subarctic Warfare

     Bernard Ross

     November 1965

     UNCLASSIFIED

     Laboratory research was conducted 17 May 1965 to 1 November 1965. Laboratory impact tests were made on floating fresh water and sea water ice slabs at varying temperatures. Penetrator diameters varied from 5/16 inch to 1-1/4 inch.

3.   U-193477   SRI-NWRC 3072
      Stanford Research Institute, Menlo Park, California
      Penetration Studies of Ice with Application to Arctic and Subarctic Warfare
      Bernard Ross
      May 1967
      UNCLASSIFIED

      In Phase II experiments, higher impact velocities were obtained with rifle
powered projectiles and laboratory sea ice slabs were frozen in place over a larger
volume of sea water to simulate Arctic sea ice. All laboratory tests were
conducted at below freezing ambient temperatures. Field tests at Point Barrow,
Alaska on Arctic sea ice were made with a rifle powered projectile test set-up and
a gun powered test rig which could fire a larger and heavier projectile. Theory
was produced for cratering which occurred at impact and for cylindrical conical
shear plugs which were produced as a consequence of perforation. In both
laboratory and field tests, it was found that there was an advantage in penetration
of the conical nose. Another finding indicated that the presence of snow cover
could affect the penetration and performance capability of a blunt projectile.

4.   U-225452   SRI-NWRC-7000-462-4
      Stanford Research Institute, Menlo Park, California
      Penetration Studies of Ice with Application to Arctic and Subarctic Warfare
      Bernard Ross and Sathya Hanagud
      September 1969
      UNCLASSIFIED

      The work was performed between 1 June 1967 and 1 July 1969 and is denoted
Phase III Study. Theoretical studies concerning the mechanics of penetration and
perforation of Arctic sea ice subjected to projectile impact were studied with the
aid of a two-dimensional, large deformation, dynamic, elastic-plastic computer code
(CANDIA CODE) which was developed in the investigation.

5. U-323368   SC-DR-70-483
    Sandia National Laboratories, Albuquerque, New Mexico
    The Development of a Sea Ice Penetrometer
    C. W. Young and J. L. Kiker
    August 1970
    UNCLASSIFIED

    A sea ice penetrometer was developed for the U.S. Coast Guard to measure the
thickness of sea ice remotely. A series of seven drop tests were performed in
February 1970 in fast winter ice at the Bay of Port Clarence, Alaska. Test data,
results and conclusions are included in the report.

6. U-251984   SRI-NWRC-7000-452-5
    Stanford Research Institute, Menlo Park, California
    Penetration Studies of Ice with Application to Arctic and Subarctic Warfare
    Bernard Ross, Sathya Hanagud, Gursharan Sidhu
    April 1971
    UNCLASSIFIED

    The report covers work performed between 1 July 1969 - 31 December 1969 and
15 April 1970 - 31 June 1970 and designated, unofficially, Phase IV Study.
Penetration problems were treated by a deep penetration theory based on dynamic
spherical cavity expansion analysis. Finite compactibility and permanent
deformation of both snow and sea ice materials were taken into account by assuming
a locking approximation for behavior under hydrostatic stress, and response as an
elastic-plastic, linear strain hardening solid under shear stress. Perforation
problems were studied with the aid of the previously developed CANDIA CODE.
Axisymmetric dynamic stress distributions were studied under conditions of impact
at normal incidence for a cylindrical blunt end projectile and a sea ice target
slab.

7.   NOL TR 71-71

     Naval Ordnance Laboratory, White Oak, Maryland

     Proceedings of the Conference on the Naval Minefield (14th):   Ice Cover

     A. H. Peale

     April 1971

     SECRET

     The general theme of the fourteenth conference was ICE COVER. The report is a
compilation of papers which were submitted for use in connection with the
conference. The theme of Session IV of the conference was PENETRATION. Explosive
cratering and perforation of ice were discussed, also elastic behavior of ice and
the development of a sea ice penetrometer.

8.   U-275475   DREV TN 1909/71

     Defense Research Establishment, Valcartier, Quebec

     Design of a Large Shaped Charge Suitable for the Perforation of Arctic

     Sea-Ice

     J. M. Jones

     May 1971

     UNCLASSIFIED

     A large shaped charge was designed which was intended to perforate thick
Arctic sea ice for the deployment of oceanographic instrumentation. A 12 inch
diameter shaped charge weighing 25 pounds was capable of penetrating 11 feet into
polar ice giving a minimum hole diameter of approximately 3.8 inches. The design
met the application requirements but it was believed that cost and convenience
requirements would limit its use.

9. U-323369   SC-DR-71-0729

    Sandia National Laboratories, Albuquerque, New Mexico

    An Air-Dropped Sea Ice Penetrometer

    C. W. Young and L. J. Keck

    December 1971

    UNCLASSIFIED

Drop tests were conducted in sea ice in the Arctic during April 1971 to proof test the sea ice penetrometer developed for the U.S. Coast Guard. The tests were conducted in annual sea ice (6 feet thick) near Thule Air Base, Greenland; in pack ice (more than 10 feet thick) and in freshwater ice near Alert, Canada and in refrozen leads between Thule and Alert. A total of 26 drop tests were made. It was reported that ice thickness was determined within an accuracy of $\pm$ 3 inches. It was determined that if the angle between the ice surface and the velocity vector of the penetrometer is greater than 40 degrees the penetrometer will penetrate the ice. For angles less than 40 degrees the penetrometer will ricochet or broach from the ice.

10. U-257713   SC-DR-72-0379

    Sandia National Laboratories, Albuquerque, New Mexico

    A Parametric Study of an Ice Penetrating Sonobuoy Vehicle

    C. W. Young

    July 1972

    UNCLASSIFIED

A study was made of the parameters affecting the design and implant performance of an ice penetrating sonobuoy vehicle. The study included the various relationships between vehicle shapes and weights (up to 100 lbs.), sea ice thickness (up to 10 feet) and penetration impact angles and velocities (from 300 to 600 feet per second). A proposed configuration was recommended for further investigation.

11. Letter to Naval Ordnance Laboratory (Mr. M. M. Kleinerman)
     Sandia Laboratories, Albuquerque, New Mexico
     Status Report on Ice Penetration Studies
     C. Wayne Young
     January 2, 1973
     UNCLASSIFIED

     The letter is a status report and planning document including status of Ice
Sonobuoy studies, Ice Penetration studies, plans and preparation for the Arctic
tests near Thule Air Base, Greenland in April 1973. Hardware to be tested included
ice penetrating sensor vehicles, ice penetrators of varying sizes and shapes plus a
scale model of a blunt bottom mine shape.

12. Letter to Naval Ordnance Laboratory (Mr. M. M. Kleinerman)
     Sandia Laboratories, Albuquerque, New Mexico
     Final Report on Ice Penetration Test of QUICKSTRIKE Configuration
     C. Wayne Young
     July 27, 1973
     UNCLASSIFIED

     The letter includes data and conclusions concerning the April 1973 Arctic test
of an ice penetrator which was a scaled model of a blunt bottom mine configuration.

13. C-273494   SLA-73-0754
     Sandia Laboratories, Albuquerque, New Mexico
     Development of an Ice Sonobuoy Penetrator (U)
     C. W. Young
     December 1973
     CONFIDENTIAL

     The report describes complete development tests to date including local tests
in soil, water and thin ice plus data and test results of successful Arctic
feasibility tests near Thule Air Base, Greenland in April 1973.

14. C-276929   SLA-74-0022
     Sandia Laboratories, Albuquerque, New Mexico
     Penetration of Sea Ice by Air-Dropped Projectiles
     C. W. Young
     March 1974
     CONFIDENTIAL

     A study of the phenomenon of ice penetration was conducted for the Naval
Ordnance Laboratory. The objective was to develop an understanding of the
phenomenon so that ice penetration characteristics of ordnance items could be
predicted. Ten ice penetration tests in the Arctic in April 1973 provided
deceleration during penetration data for penetrators of various sizes and nose
shapes. Test data from two previous Arctic tests were also used in the analysis.
In Appendix (C) of the report, data from the February 1970 Arctic tests are
summarized and data from the April 1971 Arctic tests are summarized in Appendix
(D). After analysis, it was concluded that the effects of both nose shape and
impact velocity on ice penetration were the same as previously determined in the
development of earth penetration technology. Earth penetration empirical equations
required modification for the importance of effect of the weight per unit frontal
area (W/A) of the penetrator term. A term including penetrator weight was added to
create an ice penetration empirical equation and a term involving only ice
thickness was determined to replace the "index of penetrability" used in the earth
penetration equation. Empirical equations to predict ice penetration performance
were developed for (a) depth prediction in ice when perforation does not occur, (b)
velocity of the penetrator as it exits the ice when perforation does occur, (c)
average deceleration during penetration or perforation and (d) peak deceleration.

15. Letter M1762 to Naval Ordnance Laboratory (Mr. M. M. Kleinerman)
     Sandia Laboratories, Albuquerque, New Mexico
     (Calculation of Ice Penetration Characteristics of Stockpile Mines) (U)
     C. Wayne Young
     June 14, 1974
     CONFIDENTIAL

     A brief analysis was made of ice penetration characteristics of stockpile
mines. (The letter is included as Appendix A to No. 17).

16. Letter MO3645 to Naval Ordnance Laboratory (Mr. M. M. Kleinerman)
    Sandia Laboratories, Albuquerque, New Mexico
    (Calculation of Ice Penetration Characteristics of Bomb Shapes and Mine Shapes)
    C. Wayne Young
    July 11, 1974
    CONFIDENTIAL

    Calculations were performed to predict ice penetration capabilities of the
    bomb shapes and blunt bottom mines over a range of impact velocities and impact
    angles. It was concluded that bombs should be considered as excellent candidates
    as ice penetrators within certain specified limits on impact velocity and impact
    angle. These limits would impose some limitations on release altitudes and
    velocities. Similar predictions were made for the blunt bottom mine. Observations
    relative to the next planned Arctic test program were included. (The letter is
    included as Appendix (C) to No. 17.)

17. C-297559   SAND 75-0641   •
    Sandia Laboratories, Albuquerque, New Mexico
    Sea Ice Penetration by Mk 82 and Mk 84 Bomb Shapes (U)
    C. Wayne Young
    April 1976
    CONFIDENTIAL

    A series of sea ice penetration tests were conducted near the Naval Arctic
    Research Laboratory, Point Barrow, Alaska to determine the ice perforation
    characteristics of Mk 82 and MK 84 bomb shapes. Eight inert bombs, instrumented to
    measure deceleration during ice perforation, were air dropped at selected altitudes
    and speeds to give desired impact angles. Major conclusions were that the bomb
    shapes are suitable ice penetrators, with some restrictions on release conditions
    to provide a suitable impact angle. The empirical equations for prediction of ice
    perforation performance were compared to test results.

18. C-299756   SAND 76-0113
     Sandia Laboratories, Albuquerque, New Mexico
     Arctic Tests of Ice Penetrating Sensor Vehicles
     C. Wayne Young and Louis V. Feltz
     June 1976
     CONFIDENTIAL

     Eight ice penetrating sensor vehicles were tested in 6.2 feet thick sea ice
near Point Barrow, Alaska in April 1975. The vehicle penetration characteristics
were as expected in sea ice of that thickness. Many other objectives of the test
which were demonstrated were in relation to operation of the hardware subsequent to
ice perforation.

19. Letter to Naval Surface Weapons Center (Mr. M. M. Kleinerman)
     Sandia Laboratories, Albuquerque, New Mexico
     (Penetration of Gypsite by Ordnance Items)
     C. Wayne Young
     March 7, 1977
     UNCLASSIFIED

     Three Mk 82 bomb shapes were air-dropped at White Sands Missile Range, New
Mexico in January 1977 as part of the investigation of suitability of testing
full-scale penetrators in a material having the same permeability as sea ice. It
was concluded that during the first eight feet of penetration the penetration
performance of the Mk 82 bomb in gypsite was quite similar to its expected
performance in 8 feet of sea ice and that perhaps, structural loading was slightly
more severe in gypsite. In the same test series two blunt bottom mine shapes were
dropped at different impact angles and impact velocities to investigate structural
survivability of the mine shapes. Slight bulging of the body just aft of the nose
occurred in each unit. Longitudinal and radial deceleration data were obtained.
Thickness of sea ice perforation was predicted on the basis of the gypsite
penetration measured. Further tests of bomb and mine shapes were recommended.

20. Letter to Naval Surface Weapons Center (Mr. M. M. Kleinerman)
    Sandia Laboratories, Albuquerque, New Mexico
    QUICKSTRIKE Tests at White Sands Missile Range (WSMR)
    C. Wayne Young
    August 31, 1978
    UNCLASSIFIED

    A series of penetration tests using the Mk 84 Bomb Cases were performed at
    WSMR in August 1978 using gypsite deposits to simulate thick sea ice. It had been
    previously shown that the simulation was valid for only the first few feet of
    penetration, since perforation of sea ice occurs as the ice thickness is
    penetrated. Two drops were made at 70° impact angle and three at 50° impact
    angle (50° was considered the practical limit to avoid broaching). Impact
    velocities varied in the range between 400 fps and 650 fps. Decelerations were
    measured and predictions were made of penetration performance in sea ice with some
    prediction of limitations on structural survivability.

21. Letter to Naval Surface Weapons Center (Robert Detwiler)
    Sandia Laboratories, Albuquerque, New Mexico
    (Proposed "Soft" Mine Test Plan)
    C. Wayne Young
    May 31, 1979
    UNCLASSIFIED

    A structural response test was proposed at WSMR to determine loads imposed on
    a typical "soft" moored mine structure during ice penetration. An existing (TV-8)
    structure modified to provide a conical L/d = 2 nose was proposed to measure
    stresses in the structure plus longitudinal and lateral accelerations.

22. Letter 8550 Ser. 2369 to Sandia Laboratories (C. Wayne Young)
    Naval Surface Weapons Center, Silver Spring, Maryland
    Moored Mine Ice Penetrator
    21 June 1979
    UNCLASSIFIED

    The proposed test plan was approved with modification of some details
including decreasing the planned minimum impact velocity. It was agreed that three
ballistic shapes (TV-8) would be furnished for modification and four parachutes
would be provided.

23. NSWC TR 79-323   ONR TR 79-131
    Naval Surface Weapons Center, Silver Spring, Maryland
    Arctic Mining Capabilities and Requirements (U)
    Warren H. McInteer
    August 1979
    SECRET

    A study was conducted for the purpose of providing information with which to
complete a draft operational requirement for an Arctic mine and to outline a course
of action to respond to the operational requirement. It was a joint effort of Mine
Warfare Command, Naval Surface Weapons Center, and the Office of Naval Research.
The report reviewed available environmental data from the Arctic, summarized
capabilities of existing and developmental mines in an Arctic environment and
recommended certain design requirements in order to achieve an improved capability
in Arctic mining. In the report bottom mines and moored mines were considered
separately because of differences in their capabilities to cope with the
environment. Recommendations also were not identical for bottom and moored mines.
A number of the recommendations such as: ice penetrating capacity, retardation and
delivery system requirements to achieve required impact angles and impact
velocities, etc. were specifically relevant to the purpose of this report.

24. Letter to Naval Surface Weapons Center (Mr. M. M. Kleinerman)
     Sandia Laboratories, Albuquerque, New Mexico
     (Report of "Soft" Mine Tests)
     C. Wayne Young
     July 23, 1980
     UNCLASSIFIED

     Four tests of "soft" mine penetration into gypsite simulating Arctic ice were
made at WSMR in May 1980. The test vehicles were dummy mine cases (previously
TV-8) modified by the addition of L/d = 2 conical noses. The test was planned to
simulate penetration of four feet of Arctic ice. Peak axial accelerations, peak
lateral accelerations, ʳ ᵉak bending moments and peak axial forces were determined
in the tests.

25. Internal Memorandum from U23 to U32
     Naval Surface Weapons Center, Silver Spring, Maryland
     Ice Penetration of SUBROC Depth Bomb (U)
     Glenn L. Matteson
     17 June 1982
     CONFIDENTIAL

     A study was made to determine whether the SUBROC missile could be used against
a target which was located beneath sea ice and to predict probable shock levels
induced from ice penetration. Environmental factors were based on data from No. 23
(NSWC TR79-323) and equations from No. 14 (SLA 74-0022) were utilized in
calculation of predicted penetration and shock loading.

26.   SAND 82-0599

   Sandia National Laboratories, Albuquerque, New Mexico

   Development of an Ice Penetration Model

   M. M. Hightower, F. R. Norwood and C. W. Young

   December 1982

   UNCLASSIFIED

   Various analytical methods to predict penetrator motion during normal
(vertical) impact into ice were evaluated. A constitutive equation for ice was
deduced from existing material property data and an ice penetration model was
developed. This model was used to calculate penetrator performance and loading for
several ice penetration tests. These calculations were then compared to the
experimental data.